Ground Based Stellar Interferometry at the Jet Propulsion Laboratory

Peter R. Lawson

Research and development of techniques of ground-based stellar interferometry have been ongoing at JPL since the late 1980's. The main thrust of this research has been the commissioning and testing of a new generation of interferometers for narrow angle astrometry and imaging. The ultimate goal of these projects is the support of NASA missions for the detection of extrasolar planets. In this series of four lectures I describe the theory, implementation, and development of facilities at the Palomar Testbed Interferometer and the Keck Interferometer.

Ground-Based Stellar Interferometry at the Jet Propulsion Laboratory

Part I

Palomar Testbed Interferometer

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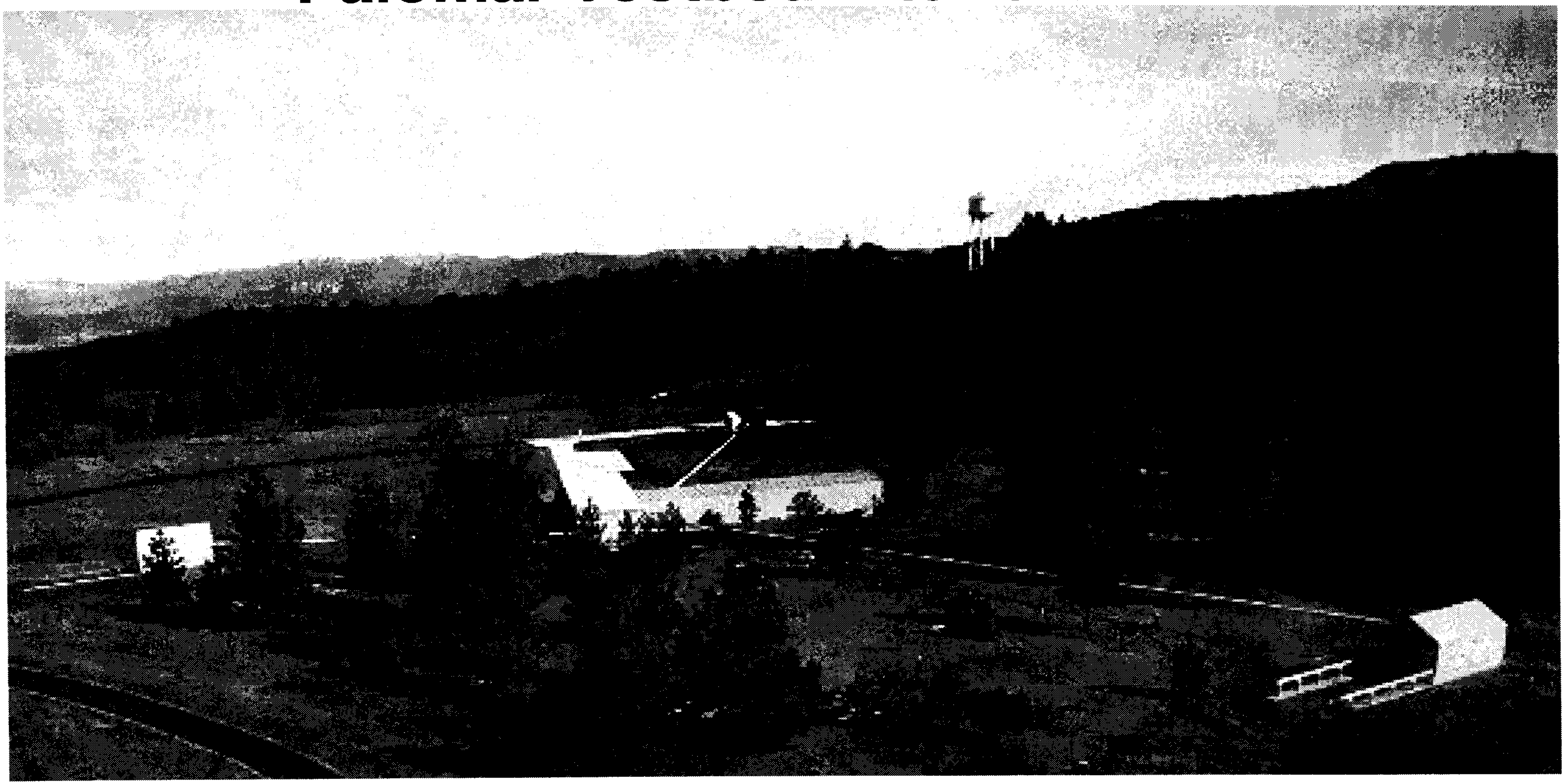
Outline

- PTI overview
- Atmospheric turbulence primer
- Detailed instrument description
- Sample measurements

Palomar Testbed Interferometer



PTI vital statistics

• Location	**Palomar Observatory**
• Baselines	**NS (110 m); NW (86 m)**
• Aperture	**40 cm**
• Delay range	**± 38.3 m**
• Architecture	**dual-star, active fringe tracking**
• Fringe tracking	**2.0--2.4 um**
• Fringe sensor	**NICMOS-3 infrared array**
• Angle tracking	**0.7--1.0 um**
• Angle sensor	**Si APD quad cell**

Objectives

- Technology development for Keck Interferometer
  - High sensitivity infrared interferometry
    - » Active fringe tracking, array detectors, active delay lines
  - Dual-star architecture
    - » Phase referencing
    - » Narrow-angle astrometry
  - Full automation
- Benefits to SIM, too
  - End-to-end interferometer operation
  - Interferometry data products
  - Common functions: fringe tracking, laser metrology, etc

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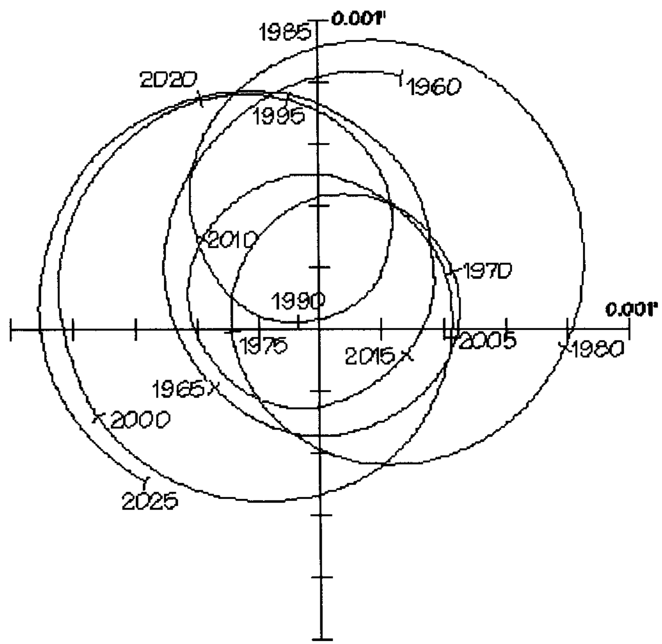
Heritage and timeline

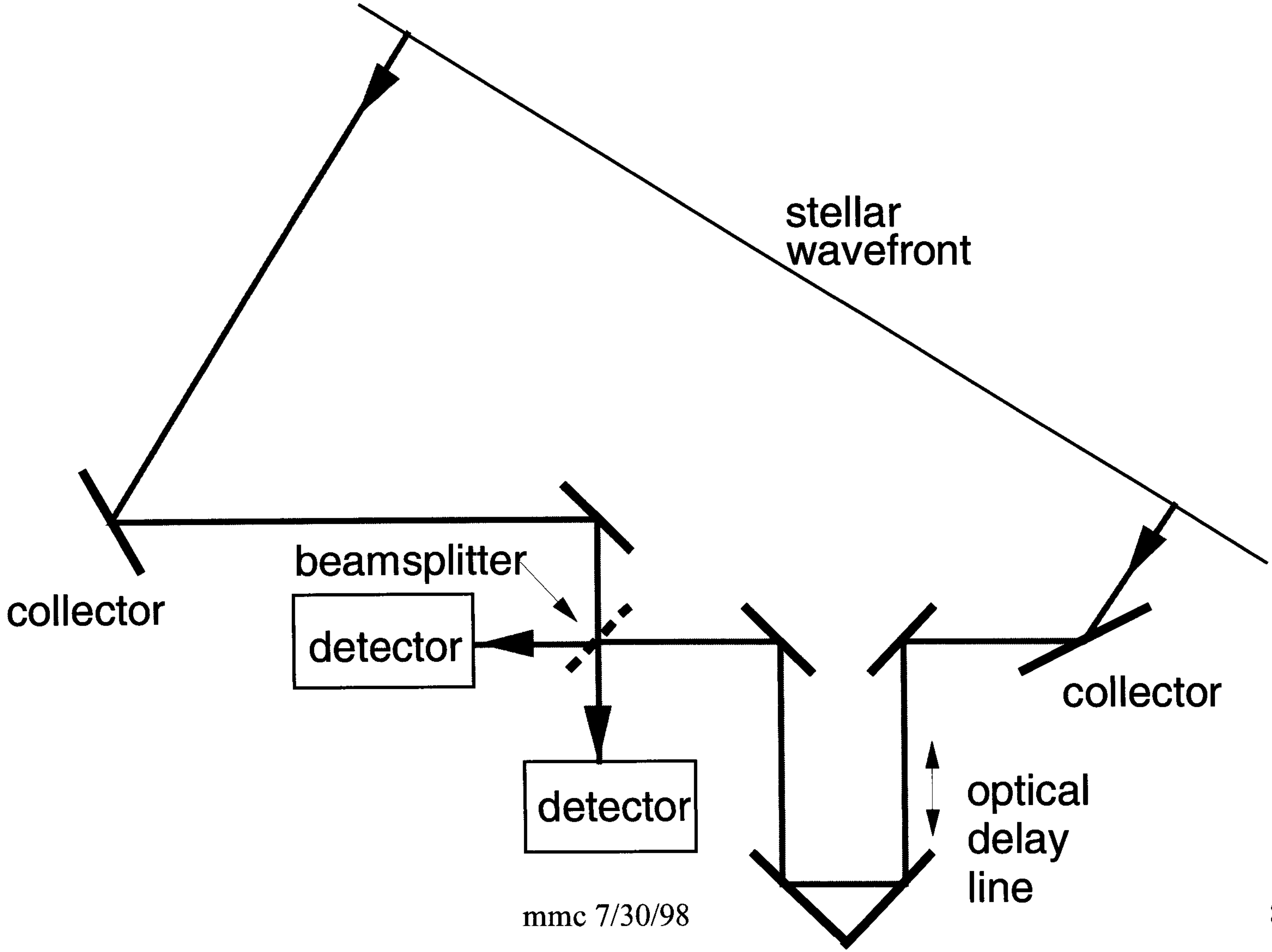
- Heritage
  - Mark III interferometer at Mt. Wilson
    - » Visible wavelength, active fringe tracking
    - » SAO, MIT, NRL, USNO
    - » Operational 1986 - 1992
- PTI timeline
  - NASA funding begins Nov 1992
  - Installation on site: spring 1995
  - First fringes: July 1995

Looking for planets with narrow-angle astrometry

- Astrometry is a complementary technique to the radial velocity method
  - Senses transverse motion
  - Gives mass unambiguously
  - Jupiter - Sun = +/- 0.5 mas at 10 pc
- Needed accuracy to conduct an interesting search
  - < 50-100 uas
- Features of the problem
  - Fundamentally narrow angle
    - » Can use angularly-nearby references



Michelson Interferometer



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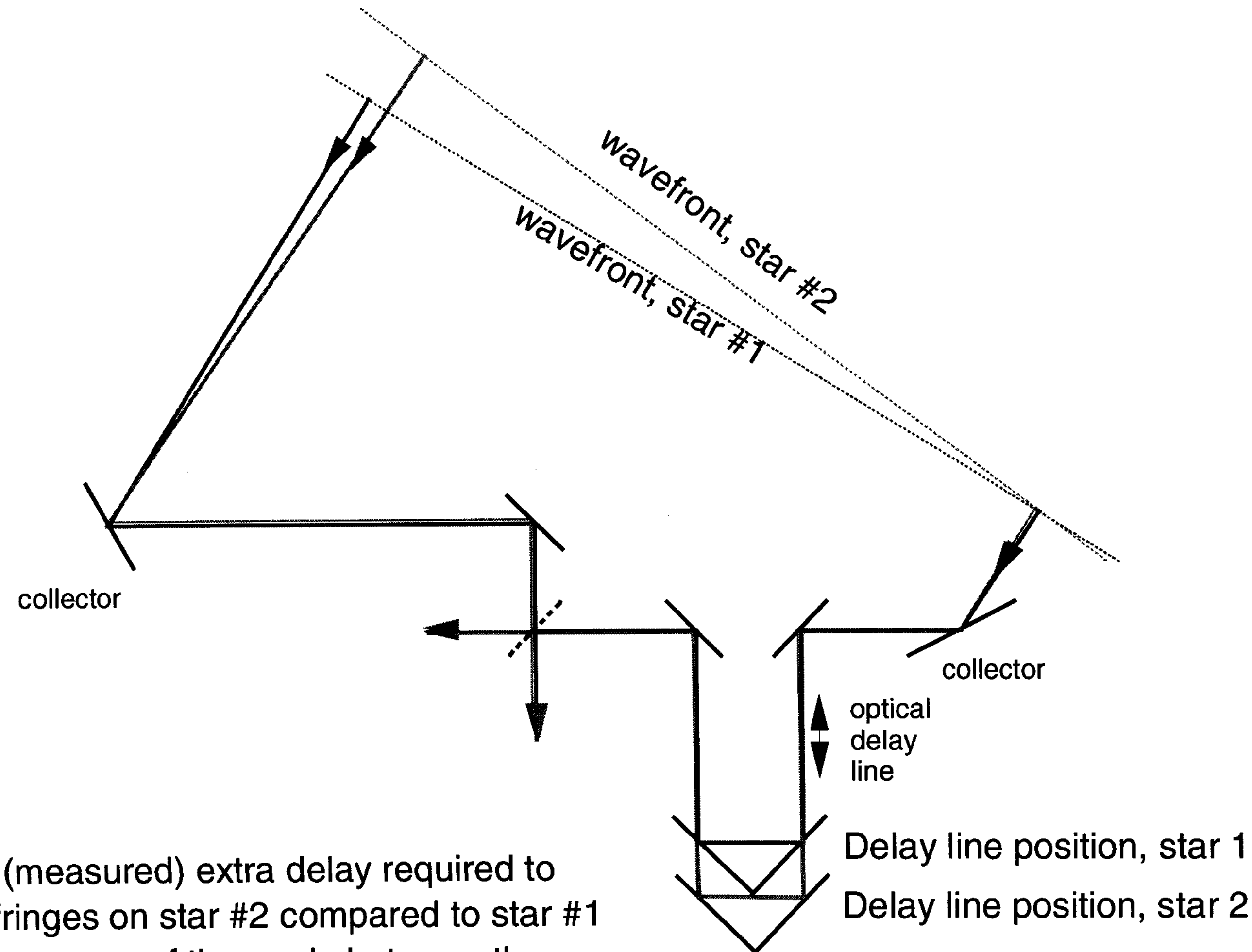
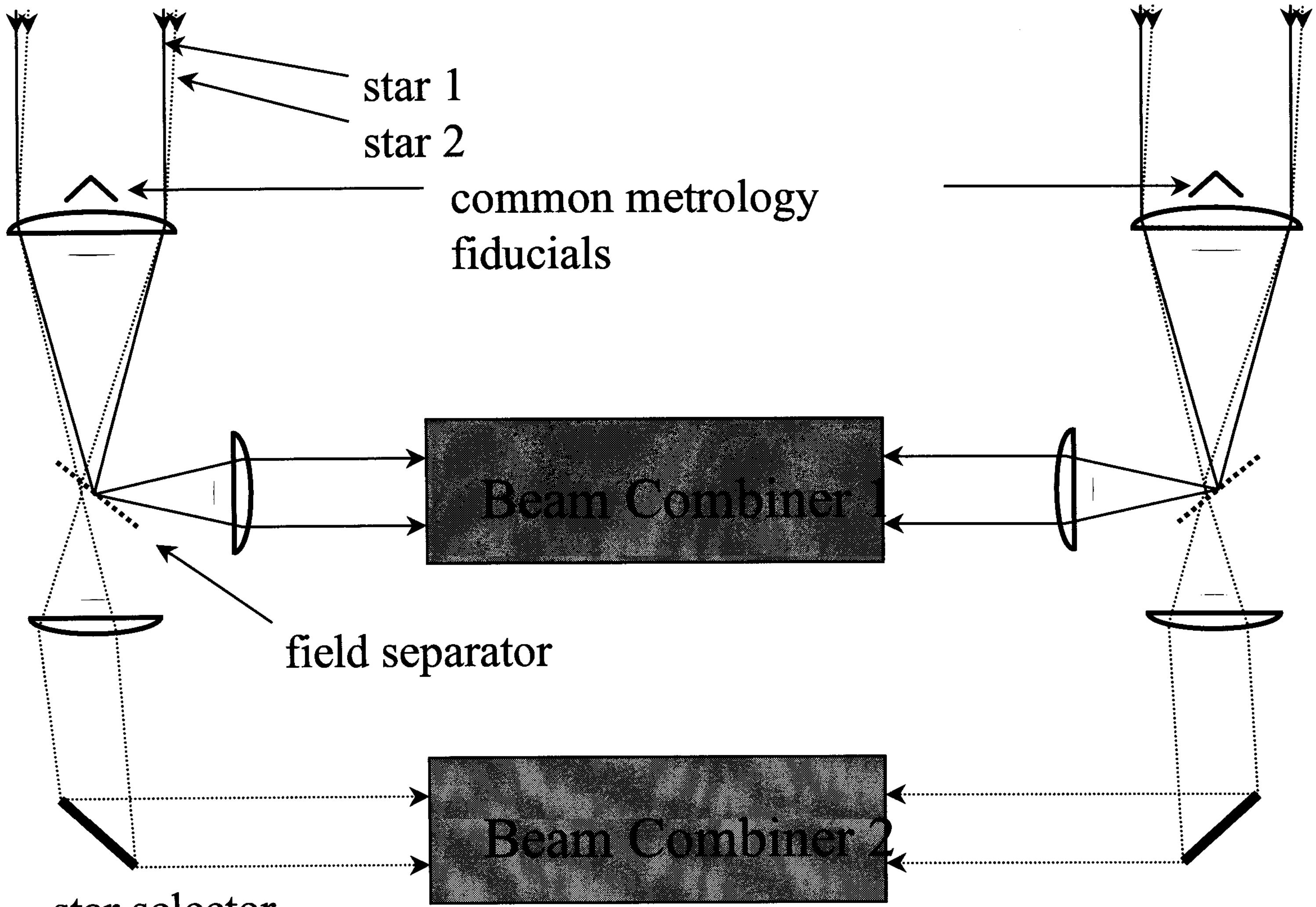
- 1) Fringe position tells us about position of source:

Astrometry with an interferometer

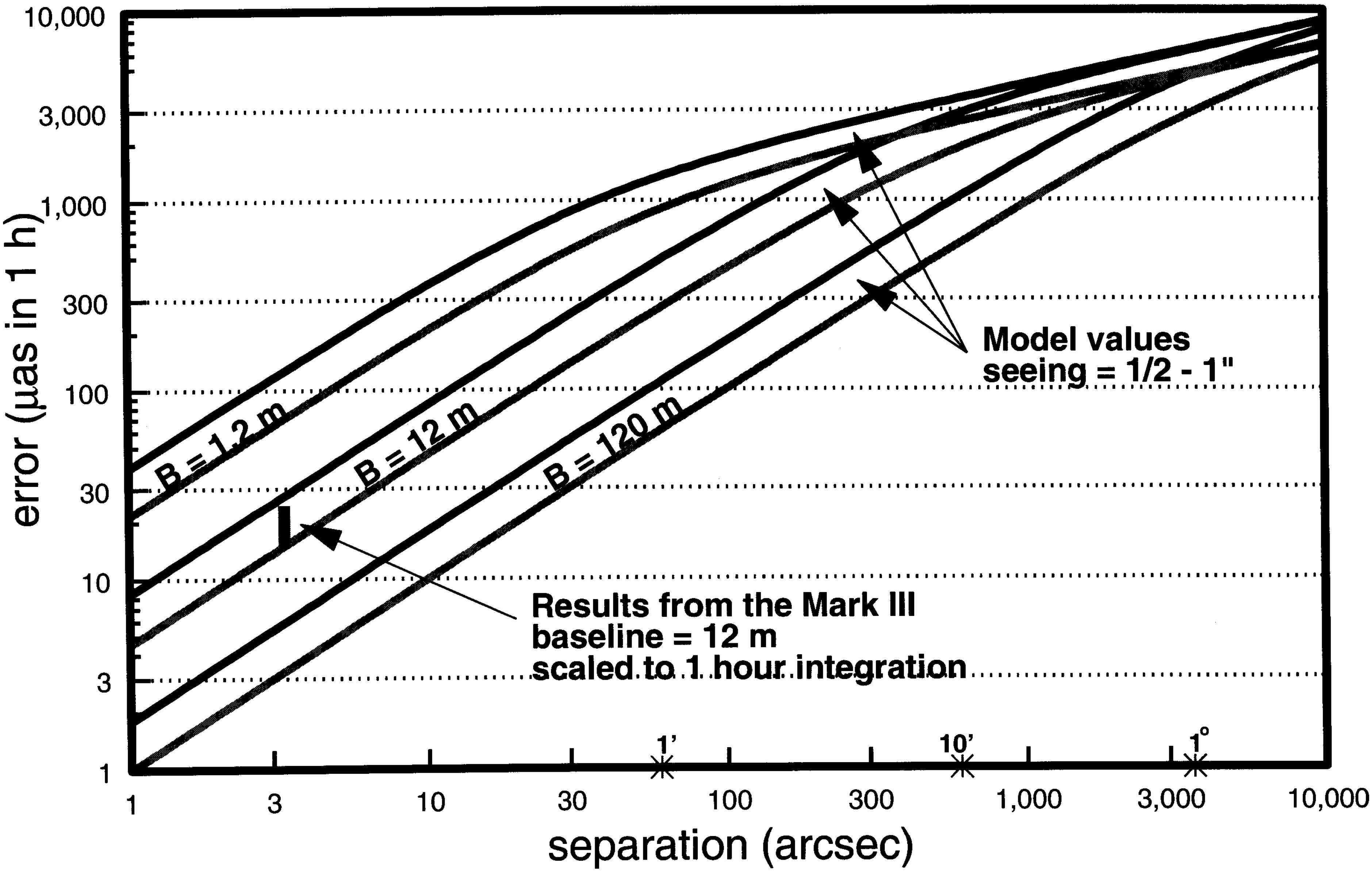


The (measured) extra delay required to get fringes on star #2 compared to star #1 is a measure of the angle between them

Dual-star concept



Atmospheric limits to a narrow-angle measurement



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Implementation dual-star astrometry, I

- Two interferometers, sharing common baseline and apertures
- Laser metrology to "tie" the two interferometers together
- "Loose" tolerance on baseline knowledge because of small sky separation

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Interferometry on the ground

- Interferometers measure coherence
  - The atmosphere is highly effective at reducing coherence
    - » It's a big, random phase screen blowing across your aperture
- Sources of coherence reduction
  - Wavefront distortion: apertures larger than $\mathbf{r_0}$ are distorted
    - » $\mathbf{r_0}$ = 10 cm at visible wavelengths
  - Fringe motion: coherent integrations longer than τ_0 get blurred out
    - » τ_0 = 10 ms at visible wavelengths
  - Angular incoherence (anisoplanatism): measurements over angles larger than θ_0 are uncorrelated
    - » θ_0 = 2-4 arcsec at visible wavelengths / 10-20 arcsec at K
- Work-arounds
  - Infrared operation
  - Adaptive optics
  - Phase referencing

Spatial effects - coherence diameter

- r_0 parameterizes atmospheric wavefront distortion
  - Wavefront distortion over an aperture $d = r_0$ in diameter is ~1 rad rms
    - » Depends on aperture as $\sigma^2 = 1.03(d / r_0)^{5/3}$ rad^2
  - Distortion is a geometric effect, i.e., add pathlength, not phase
    - » r_0 is a function of wavelength
    - » $r_0 \propto \lambda^{6/5}$
  - Seeing and r_0
    - » Long exposure image with a big telescope has a resolution of λ / r_0

Seeing	r_0 at 0.55 um	r_0 at 2.2 um
1 arcsec	10 cm	50 cm
0.5 arcsec	20 cm	1 m

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More on r_0

- Why do you care? It reduces visibility
  - $V^2 = \exp(-2\sigma^2) = \exp(-2.06(d / r_0)^{5/3})$
    - » (2 apertures, Marechal approximation)
- What can you do?
  - Work in the infrared
    - » r_0 is larger
  - Tip/tilt correction
    Ideal tip/tilt reduces error
    - from $\sigma^2 = 1.03(d / r_0)^{5/3}$ rad^2
    - to $\sigma^2 = 0.134(d / r_0)^{5/3}$ rad^2
  - Adaptive optics
    - » High-order correction of wavefront aberrations

Temporal effects - coherence time

- t_0 parameterizes the time variability of the atmospheric phase
  - Can be defined many different ways
    - » Way one: structure function
      - Definition: $D(\tau_0) = \text{variance}\{\phi(t)-\phi(t-\tau_0)\} = 1\ \text{rad}^2$
      - Time dependence: $D(t) = (t/\tau_0)^{5/3}$
    - » Way two: interval variance
      - Definition: $\sigma^2(T_0) = 1\ \text{rad}^2$
      - Time dependence: $\sigma^2(T) = (t/T_0)^{5/3}$
  - This is also a geometric effect, i.e., add pathlength, not phase
    - » $\tau_0, T_0 \propto \lambda^{6/5}$

Seeing	Wind	τ_0 / T_0 at 0.55 um	τ_0 / T_0 at 2.2 um
1 arcsec	10 m/s	2 ms / 8 ms	11 ms / 43 ms
0.5 arcsec	10 m/s	4 ms / 16 ms	22 ms / 85 ms

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More on τ_0, T_0

- Why do you care? It reduces visibility (*Everything* reduces visibility!)
  - $V^2 = \exp(-\sigma^2) = \exp(-(T/T_0)^{5/3})$
    - » (Marechal approximation)
  - Also, τ_0 sets your max sample spacing if you must phase unwrap
- What can you do?
  - Work in the infrared
    - » τ_0, T_0 are larger
  - Linear prediction
    - » Gains a little (+25% increase in effective coherence time)
  - Phase referencing
    - » Essentially, adaptive optics between interferometer apertures

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Phase referencing

- Similar to use of guide interferometers to phase SIM
- Like AO
  - AO uses a reference star (or laser guide star) to measure atmospheric wavefront distortions
  - Uses deformable mirror to correct distortion on reference star and in vicinity of reference star
- Phase referencing
  - Uses reference star (no laser tricks, unfortunately) to measure atmospheric fringe motion
  - Uses optical delay line to correct motion on reference star and in vicinity of reference star
- How is "vicinity" parameterized?

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Isoplanatic angle

- Vicinity of == in the same isoplanatic patch
  - Within the isoplanatic patch, the atmospheric effects on the stars are correlated
  - Isoplanatic angle = radius of isoplanatic patch
    - » $\theta_0 \sim 0.2 r_0 / L$, where L = "height" of turbulence
  - Also grows with wavelength...

Seeing	θ_0 at 0.55 um	θ_0 at 2.2 um
1 arcsec	2 arcsec	10 arcsec
0.5 arcsec	4 arcsec	20 arcsec

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Implementation dual-star astrometry, II

- Two interferometers, sharing common baseline and apertures
- Two stars: one bright (target w/planet, nearby); one faint (reference w/ no planet (hopefully), far away)
- Use target star as phase reference
  - Cophase (==phase reference) interferometer for stars within isoplanatic patch
- Chose reference star within isoplanatic patch of target star
- Work in the infrared (2.2 um) for its larger isoplanatic angle
  - Increases solid angle over which to find reference stars (15-20 arcsec radius)
  - Allows use of larger apertures (1.5--2.0 m with tip/tilt correction) to increase sensitivity
- Potential accuracy with 100-m baseline is 10's uas in an hour

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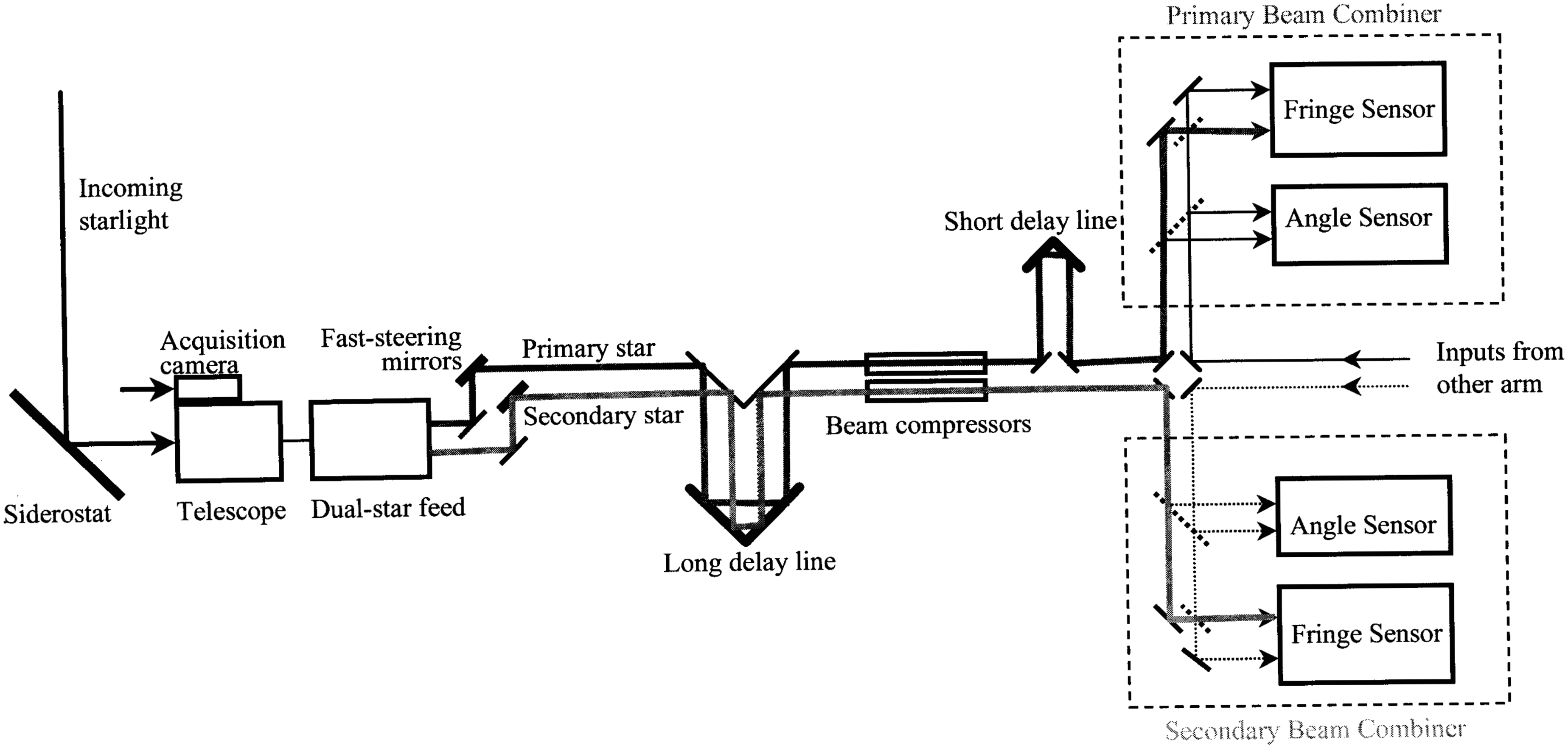
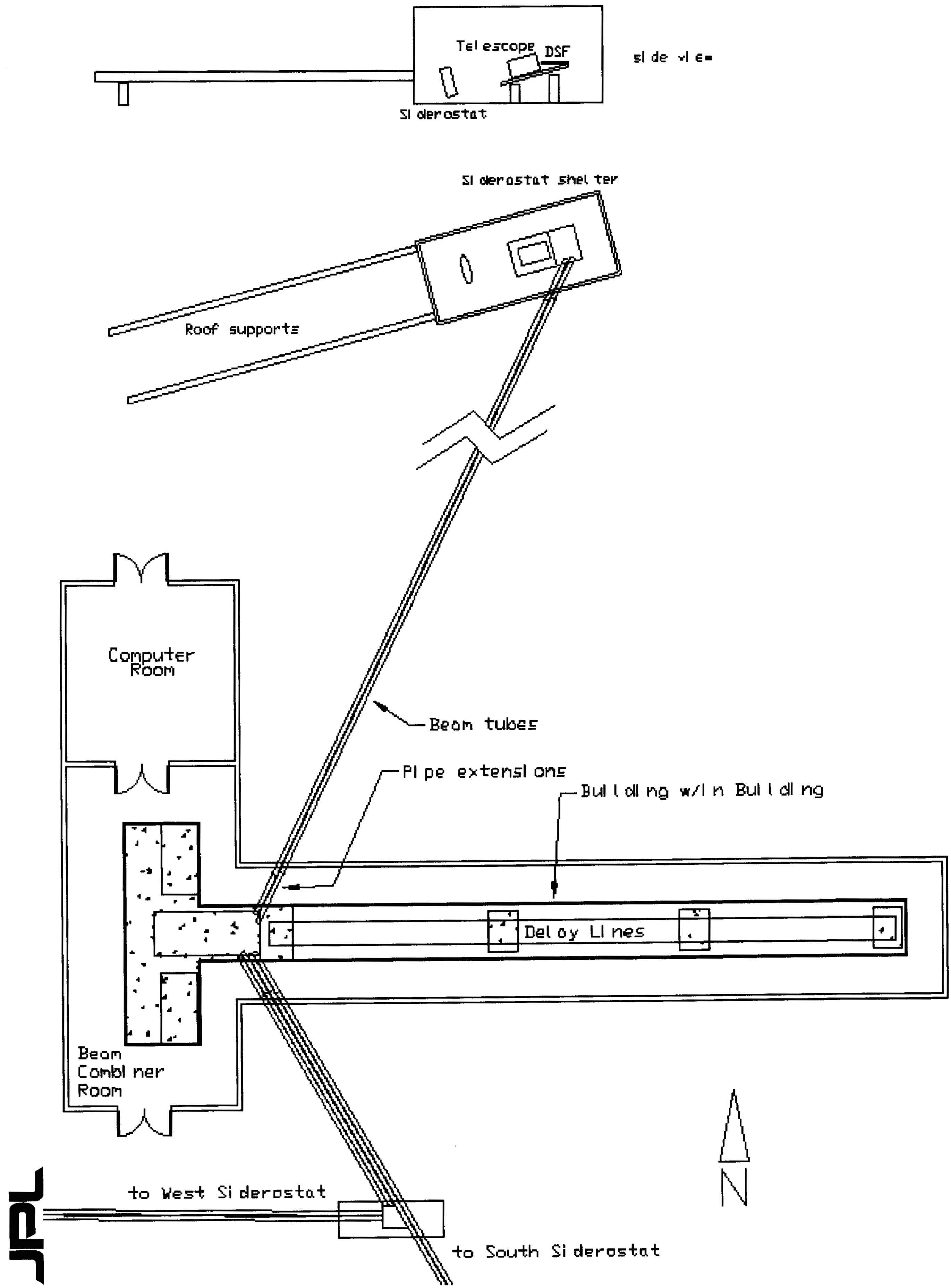
PTI block diagram





Telescope
DSF
side view
Siderostat
Siderostat shelter
Roof supports
Computer Room
Beam tubes
Pipe extensions
Building w/in Building
Delay Lines
Beam Combiner Room
N
to West Siderostat
to South Siderostat

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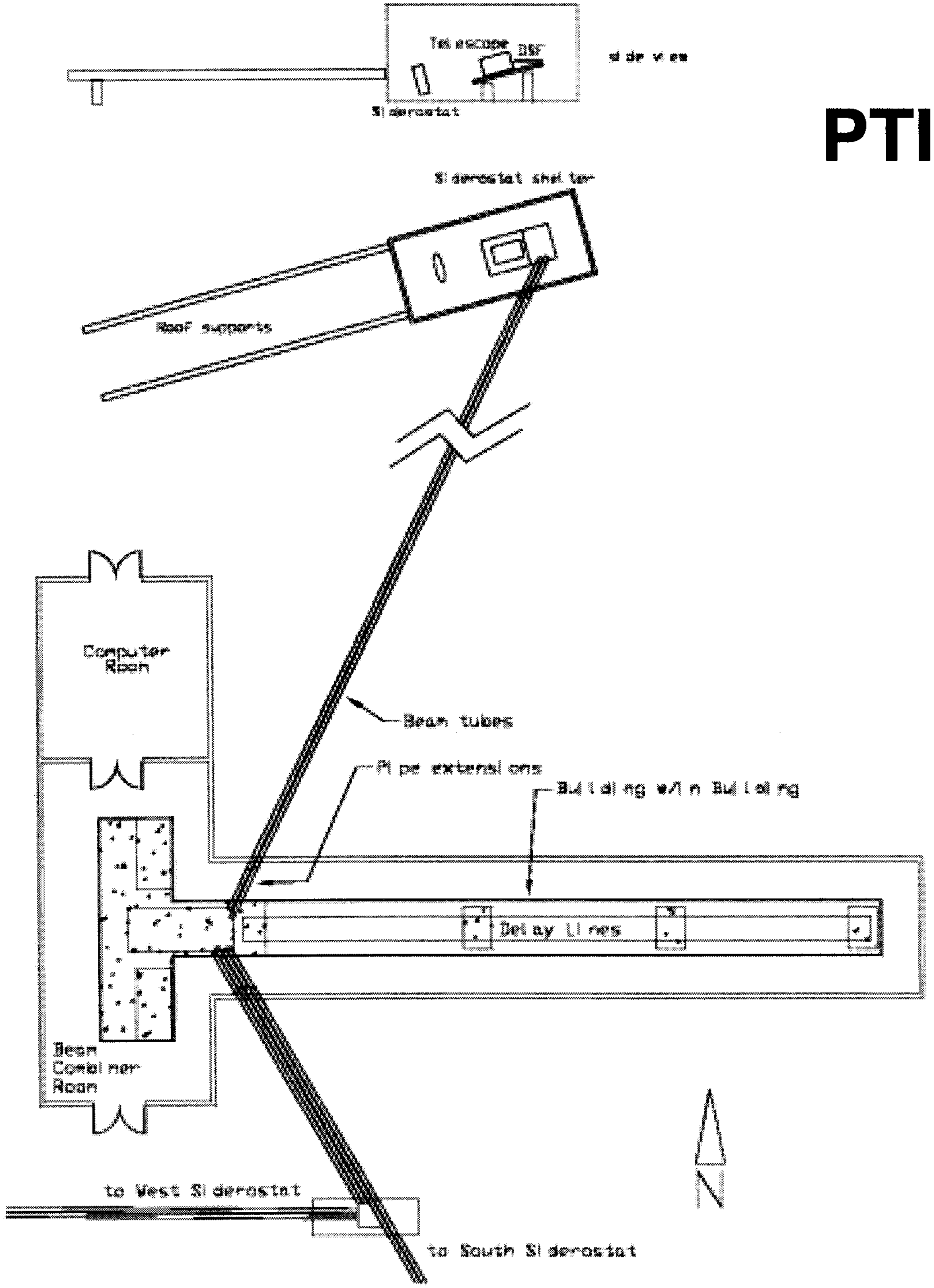
PTI layout



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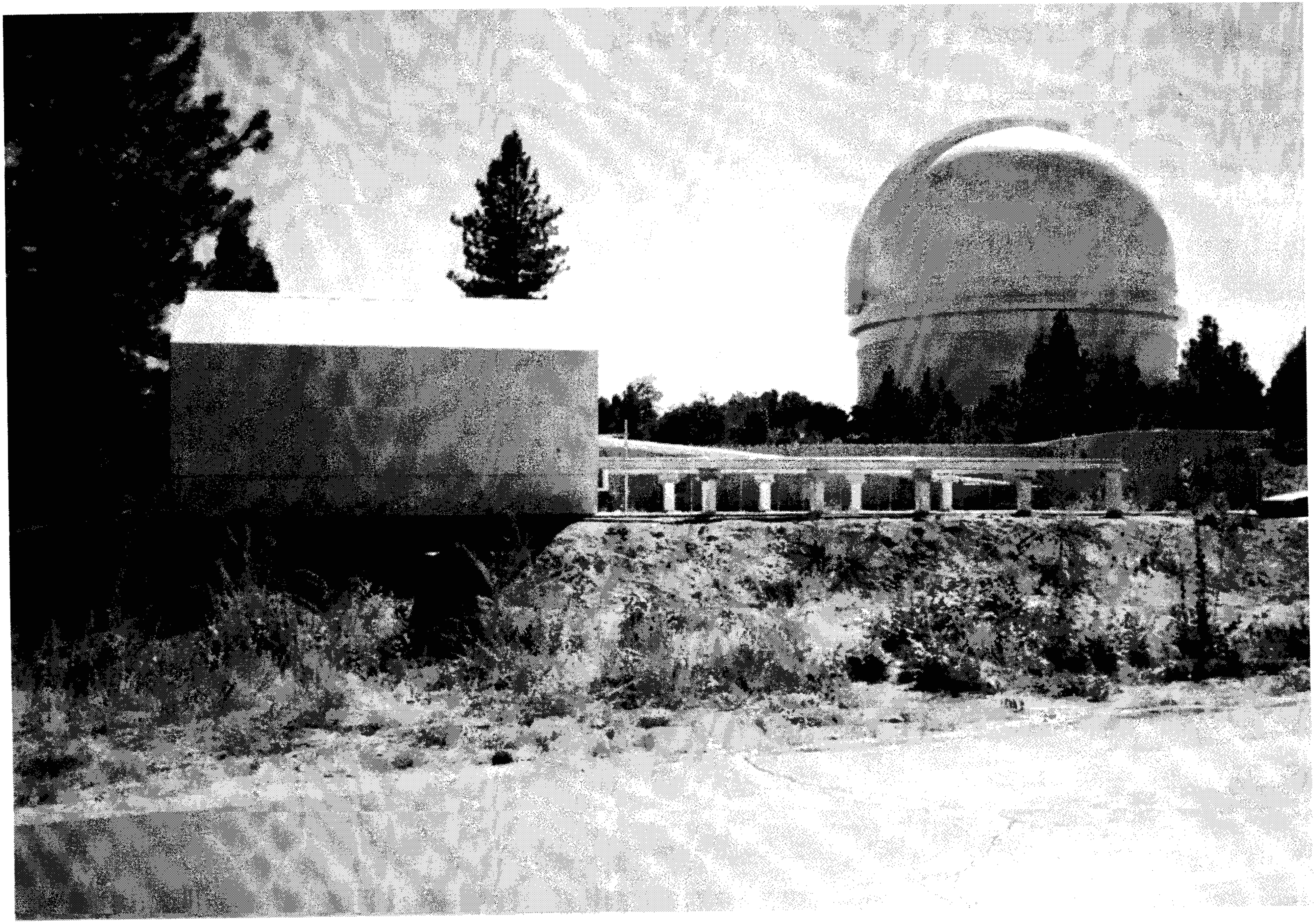
Building and site

- Modular building, 100' long
- "Building-in-a-building" for thermal control
- Beam pipes: originally air, now vacuum
  - Air OK for 2.2 um (low dispersion at that wavelength)
  - Vacuum pipes provide better metrology propagation
- Optical tables in building grouted to isolation piers; beam combiners on breadboards on tables
- Siderostat shelters are simple buildings with roll-back roofs
  - Air conditioned to match nighttime temperature



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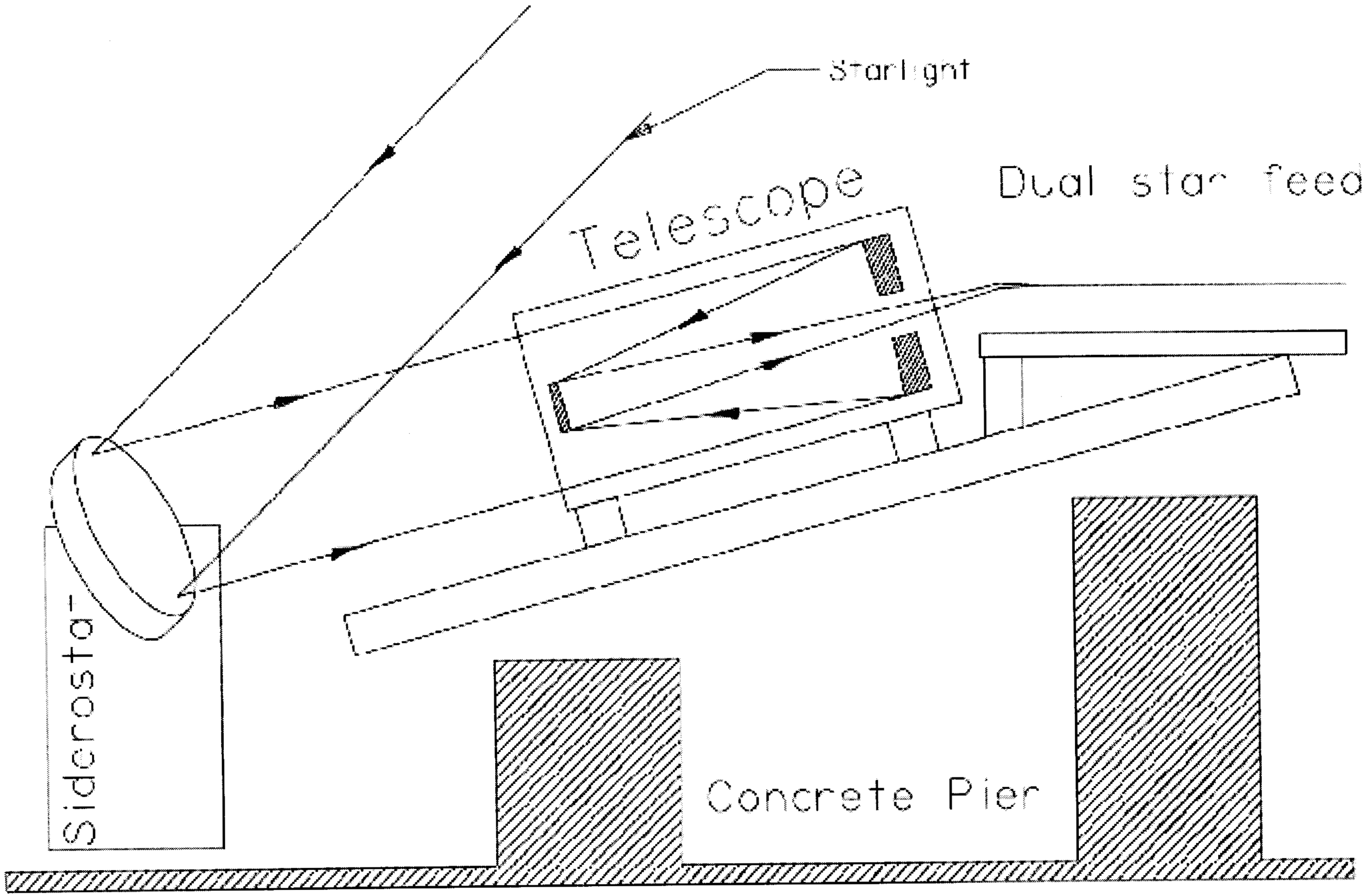
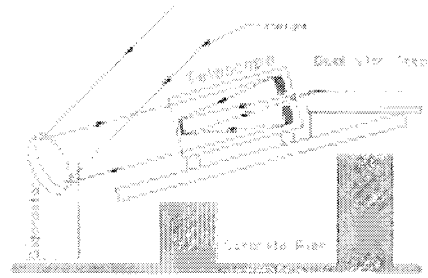
Siderostat and Telescope



Siderostat and Telescope



- Alt/Az siderostat mount moves 50-cm flat
- Mount is trimmed such that it pivots about front surface to 100 um
  - Measure distance to front (or back) of mirror with mount at 4 orientations
- Feeds fixed 40-cm telescope
  - Telescope angled downward to improve vignet-free range
    - » No vignetting east of transit
  - f/10 Cassegrain telescope forms an image of the field


MAX
MAX

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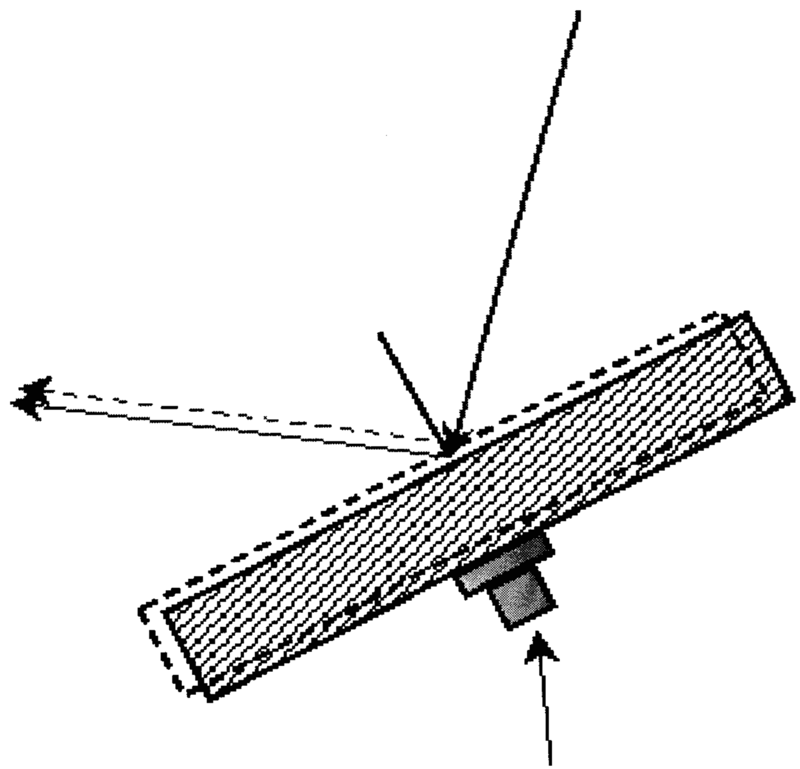
Siderostat feedforward

- Accelerometer added to sense residual piston vibrations of mirror mount
- Filtered, doubly-integrated acceleration gives high-pass jitter
- Scaled by 2 cos θ to yield effect on OPD
- Fed forward at 2 kHz to delay line for compensation



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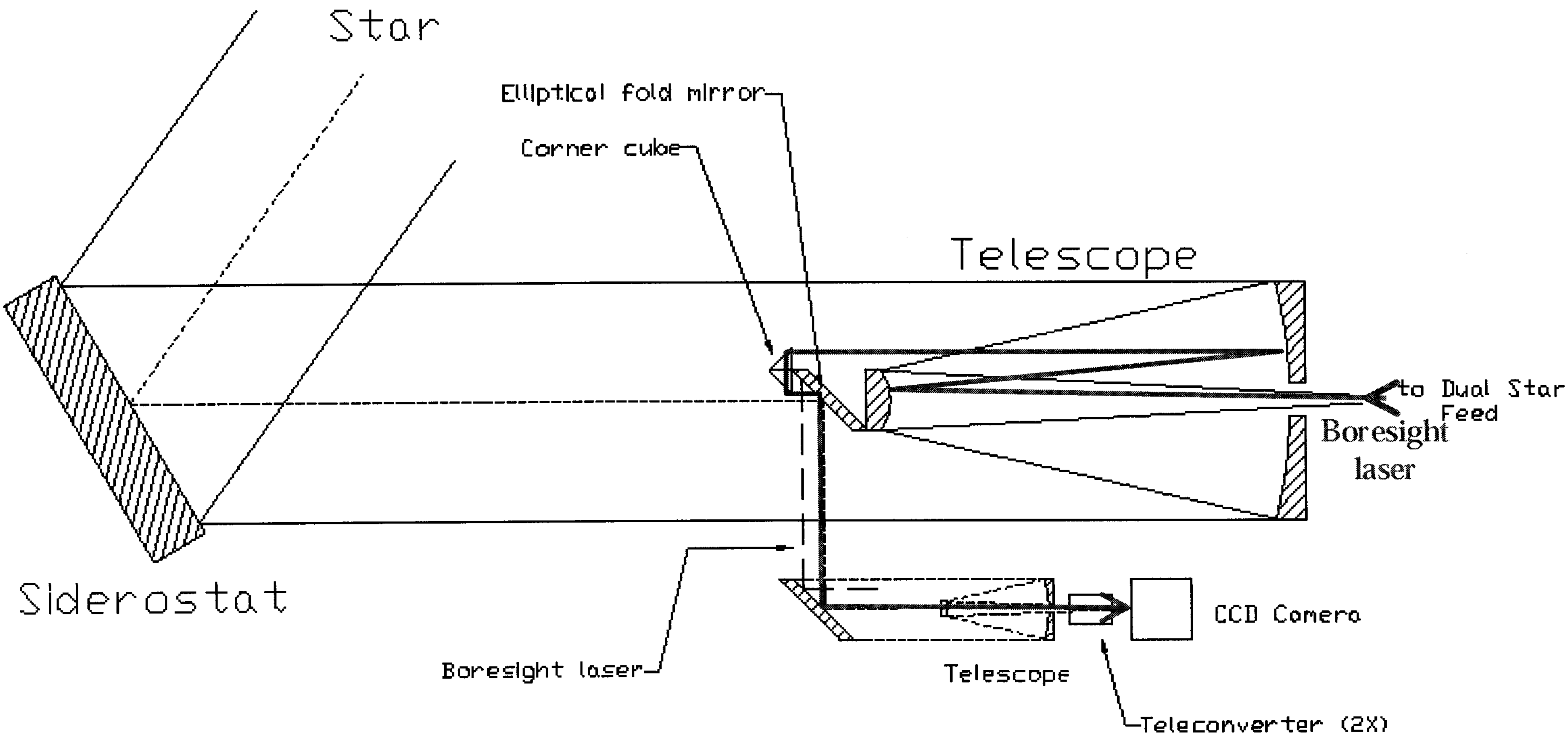
Acquisition system



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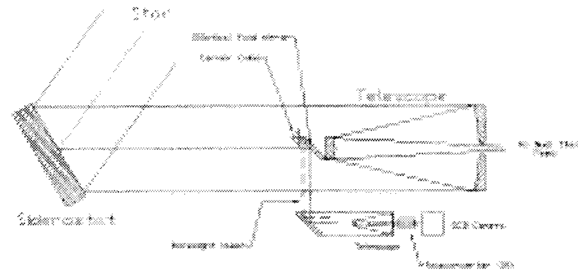
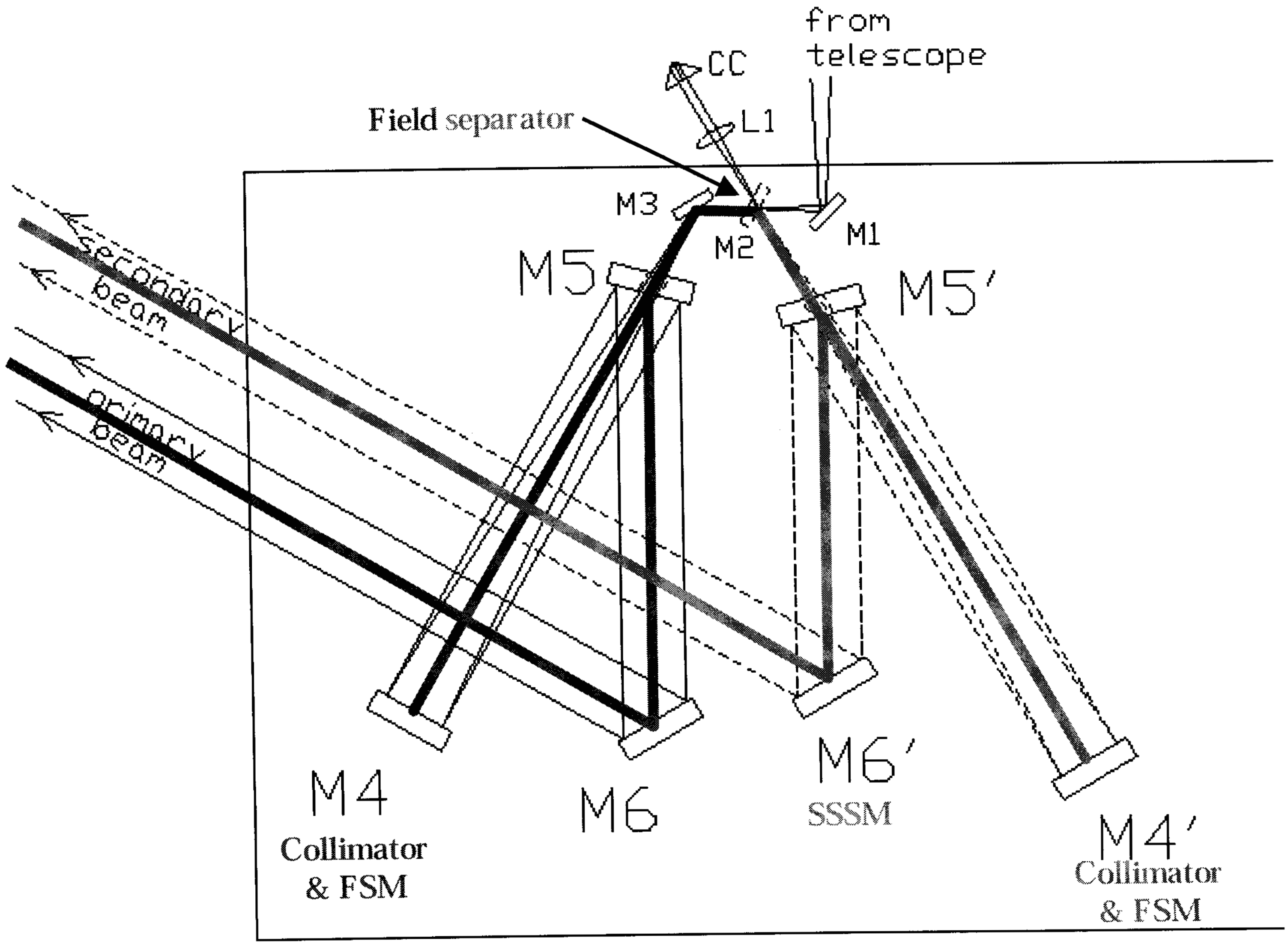
Acquisition system



- Pick off light in secondary shadow for wide-angle acquisition
- Feeds conventional CCD camera
- Automated system commands siderostat to center star image
- Calibrations: boresight laser injected from lab is redirected with corner cube into camera
  - *primary boresight*: record position of laser spot from primary table
    - » establishes where “center” is
  - *secondary boresight*: view laser spot from secondary table
    - » DSM is adjusted to align secondary spot to primary one
  - *star boresight*: record position of star after star-tracker is tracking
    - » tracks drifts in zero point; no aberrations

Dual-star feed



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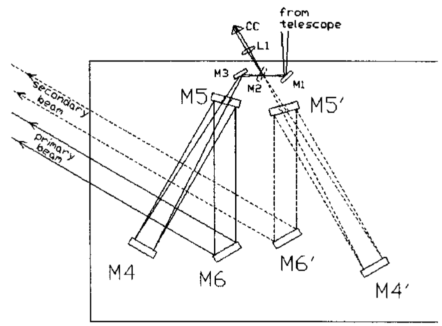
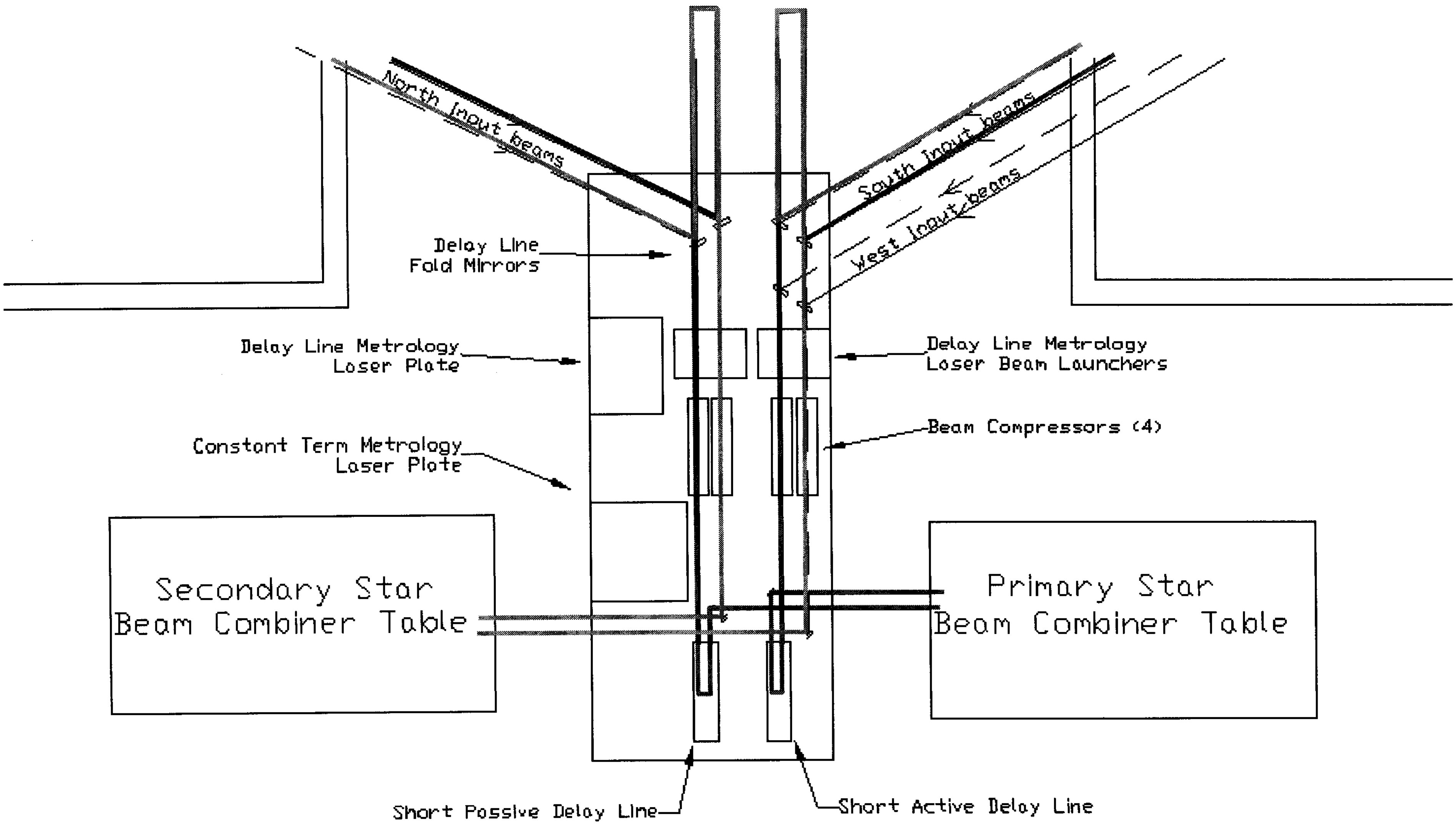
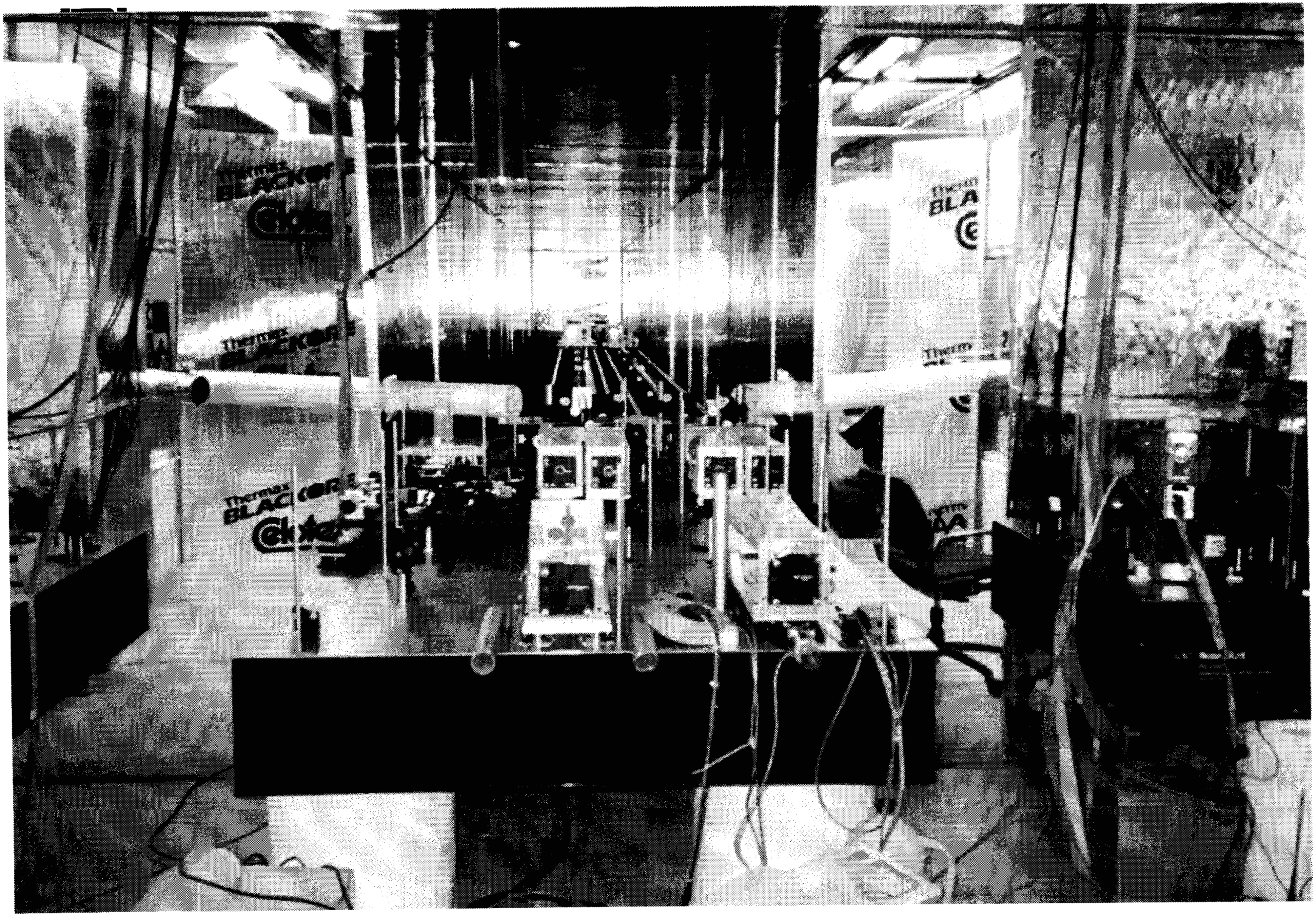
Dual-star feed



- Separates light from telescope focus into two separate collimated beams
  - Image formed on field separator (M2)
  - Primary beam recollimated by M4, directed to building by M5, M6
  - Secondary beam recollimated by M4'
    - » M6', the secondary star selector mirror (SSSM) is located at a pupil
    - » Steering the SSSM selects the secondary star within the siderostat field-of-view
  - M4 and M4' are also the fast-steering mirrors of the interferometer
    - » Flexural mirror mounts, PZT actuators
- 7.5 cm beams directed to main building

Central optics

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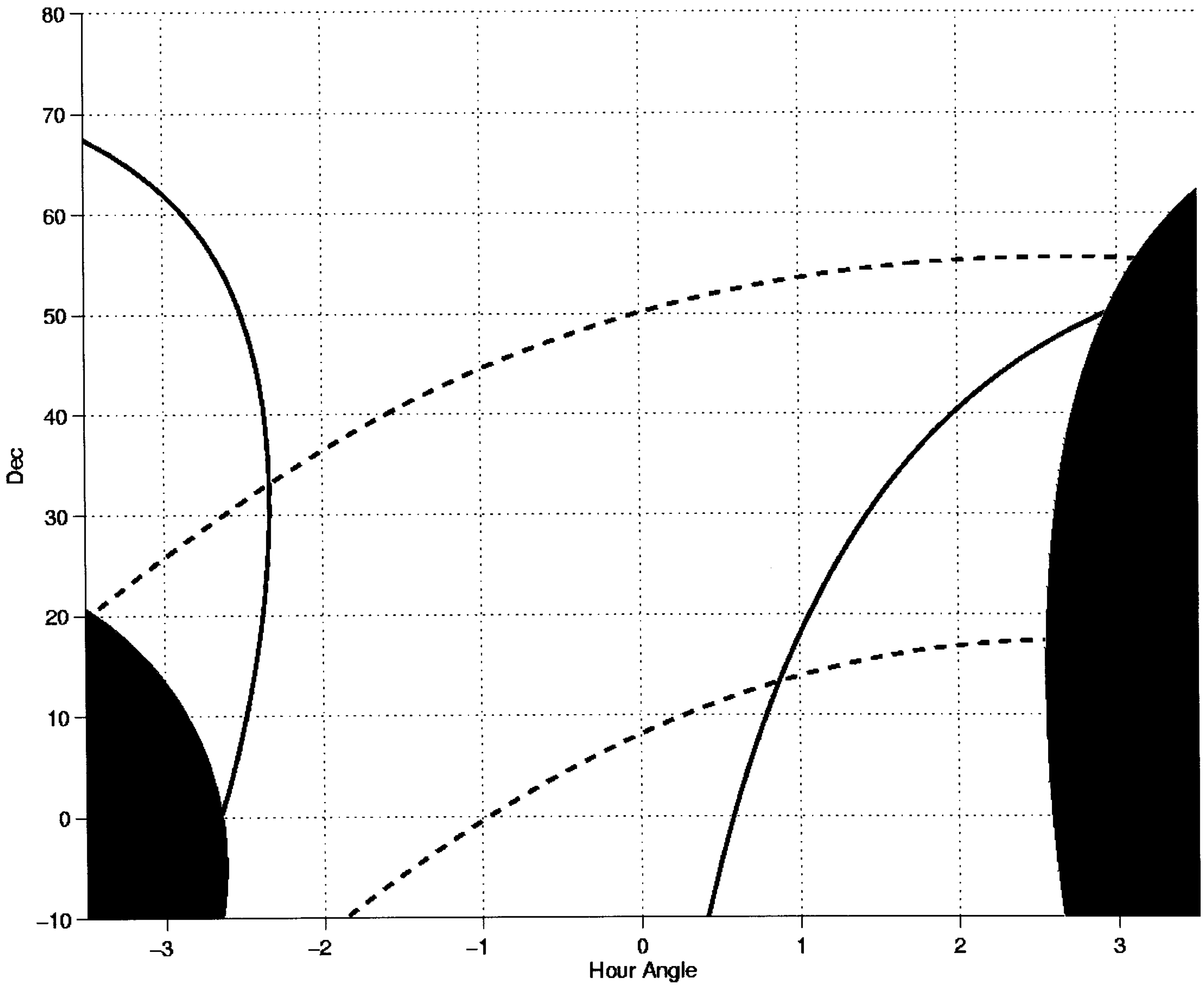
Long delay lines

- Two delay lines, each with physical travel of 19 m
  - Total delay: ± 38.3 m
    - » Sky coverage: ~40 deg in dec. for a 110-m N-S baseline
- Delay both primary and secondary 7.5-cm beams from each aperture
- Delay line design
  - Active cart (moves continually during observation): 4-stage design
    - » PZT: 30 um stroke, momentum balanced
    - » Optics voice coil: ~1 cm stroke
    - » Motor voice coil: ~1 cm stroke
    - » Motor: friction drive, 19-m range
  - Passive cart (only moved between stars): just motor
- Delay-line performance: 10-20 nm jitter at sidereal rates
  - 2 kHz servo update

PTI sky coverage



Beam compressors and small delay lines

- Beam compressors
  - Compress 7.5 cm beams to 2.5 cm to reduce size of back-end optics
    - » BTW: Rayleigh lengths (d^2/λ)
      - 2500 m for 7.5 cm
      - 280 m for 2.5 cm (somewhat marginal to use for full propagation)
- Small delay lines
  - Delay only primary beams
    - » Motor + PZT only
    - » Short range: only a need a few cm
  - I.e.
    - » Long delay lines delay both stars
    - » Small delay lines offset from primary to secondary

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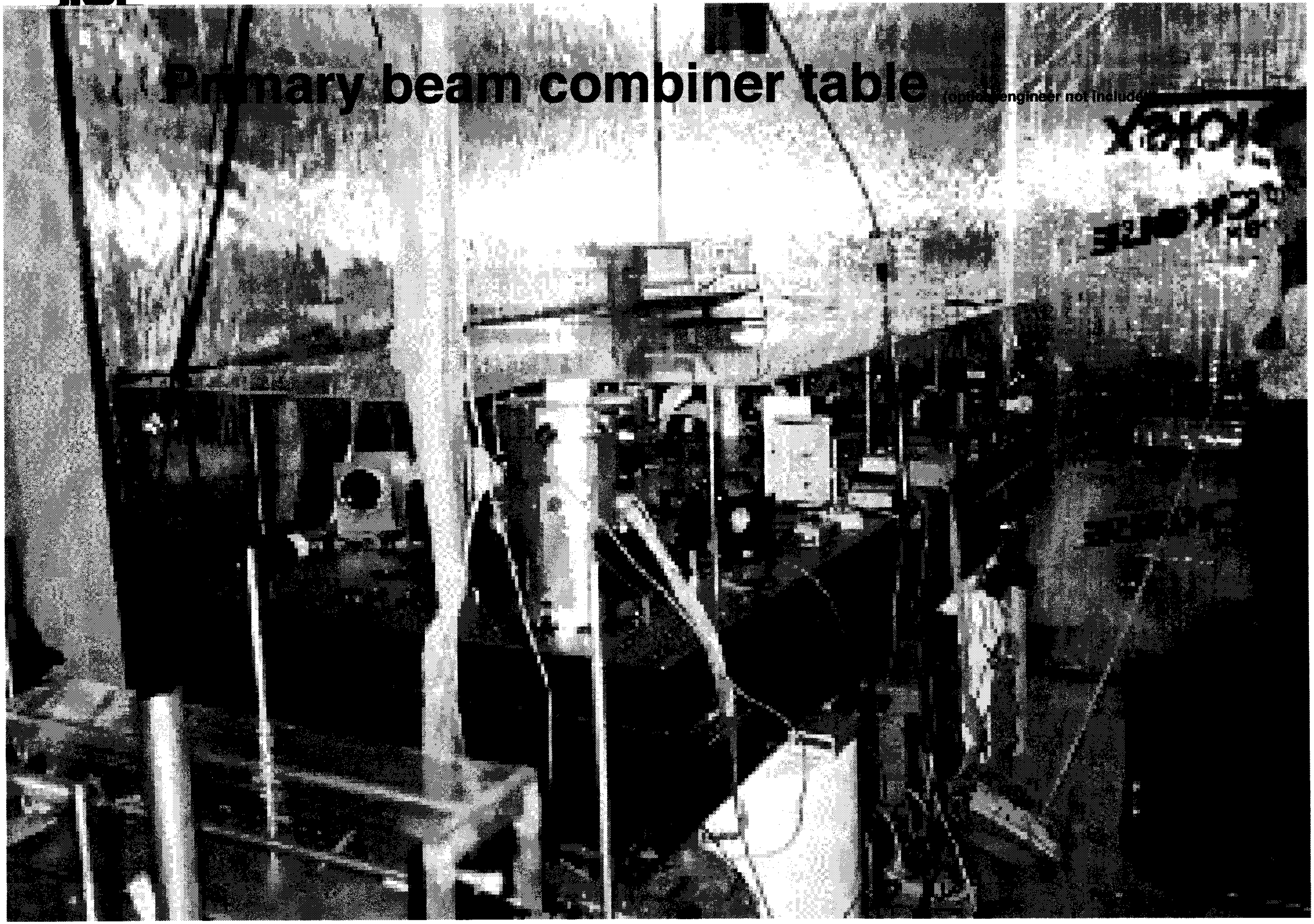
Beam combiner tables

- Contain optics for
  - Fringe tracker
  - Star tracker
  - Alignment & boresight

Primary beam combiner table (optical engineer not included)



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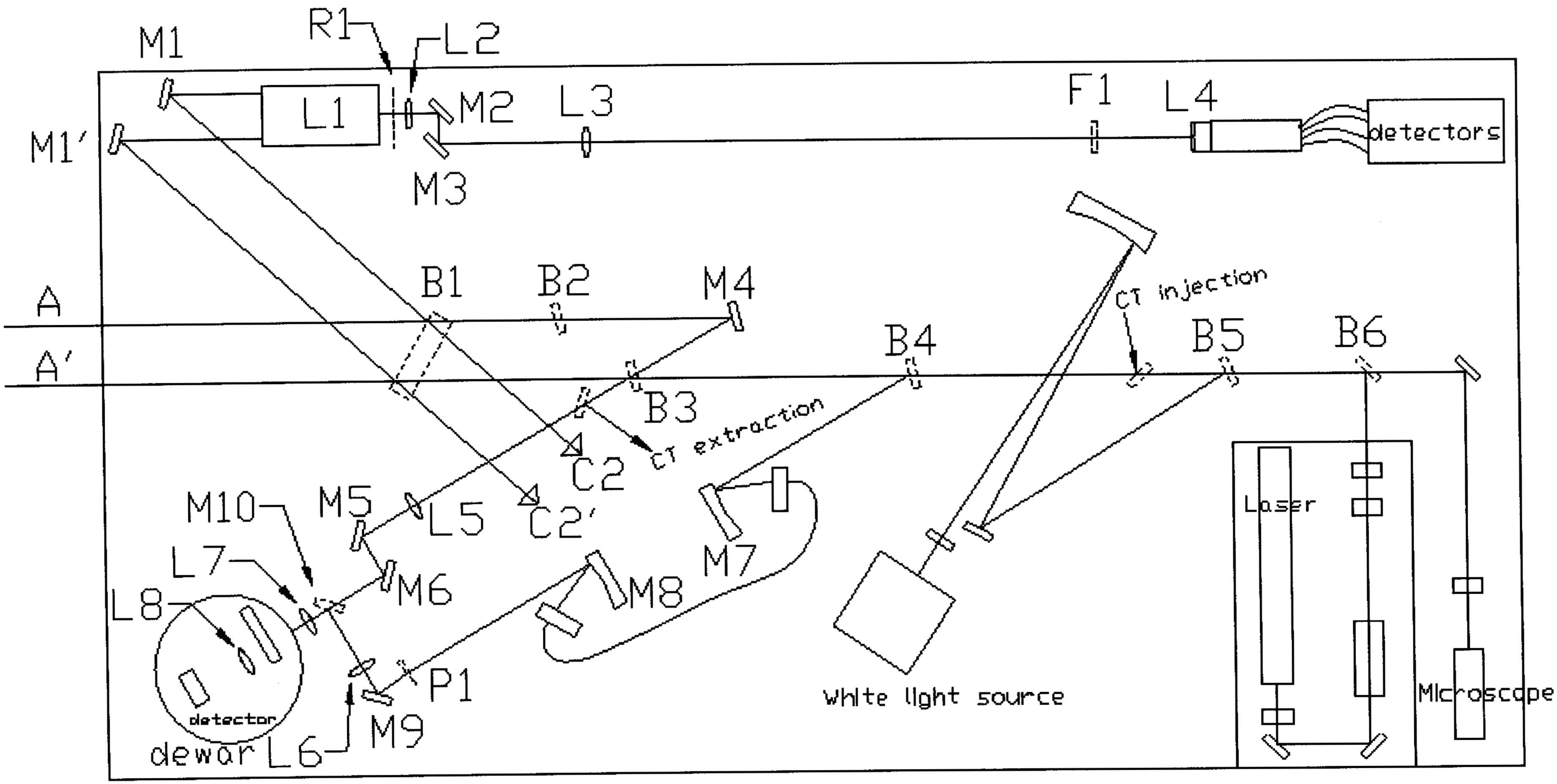
Beam combiner table



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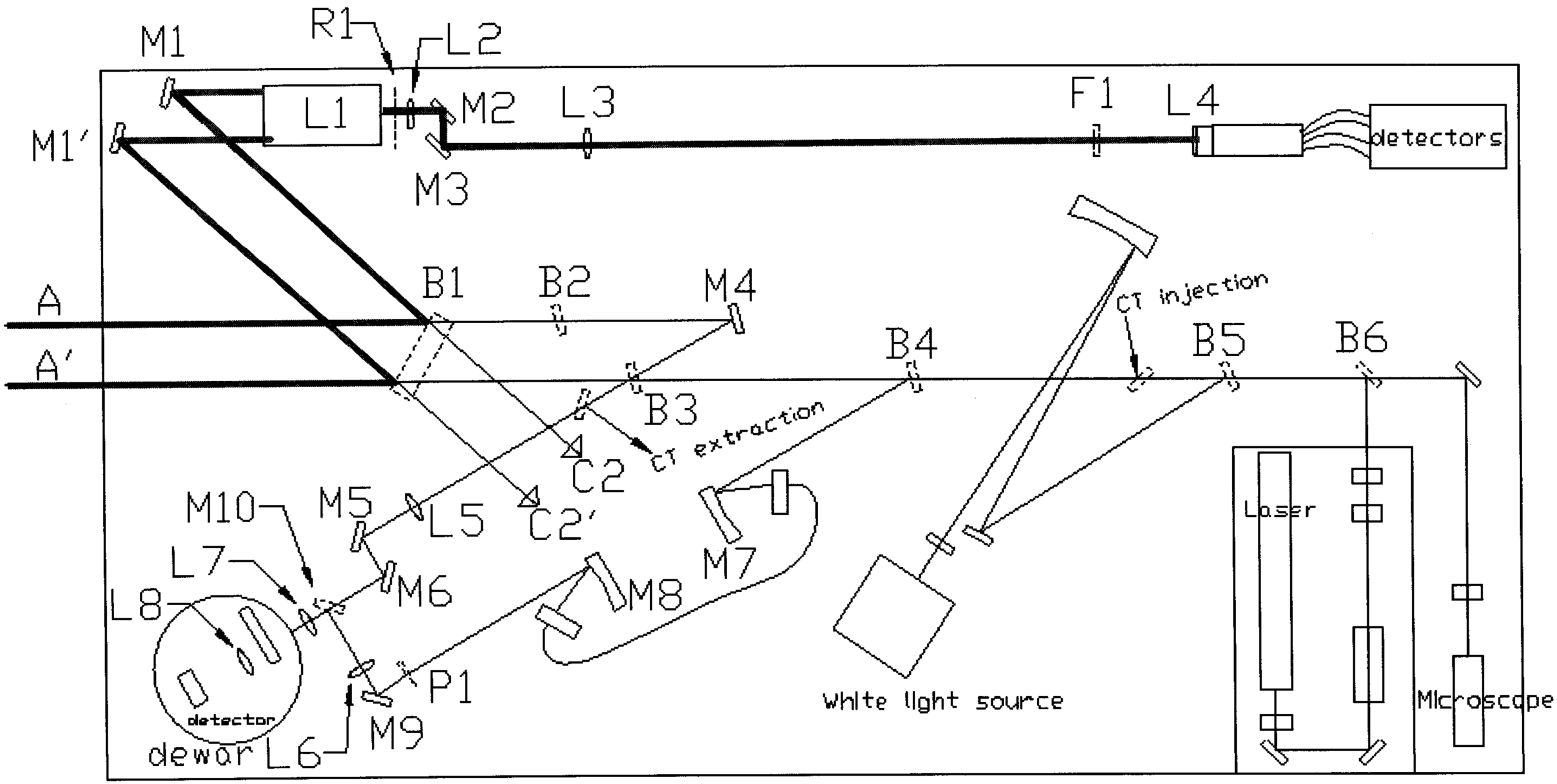
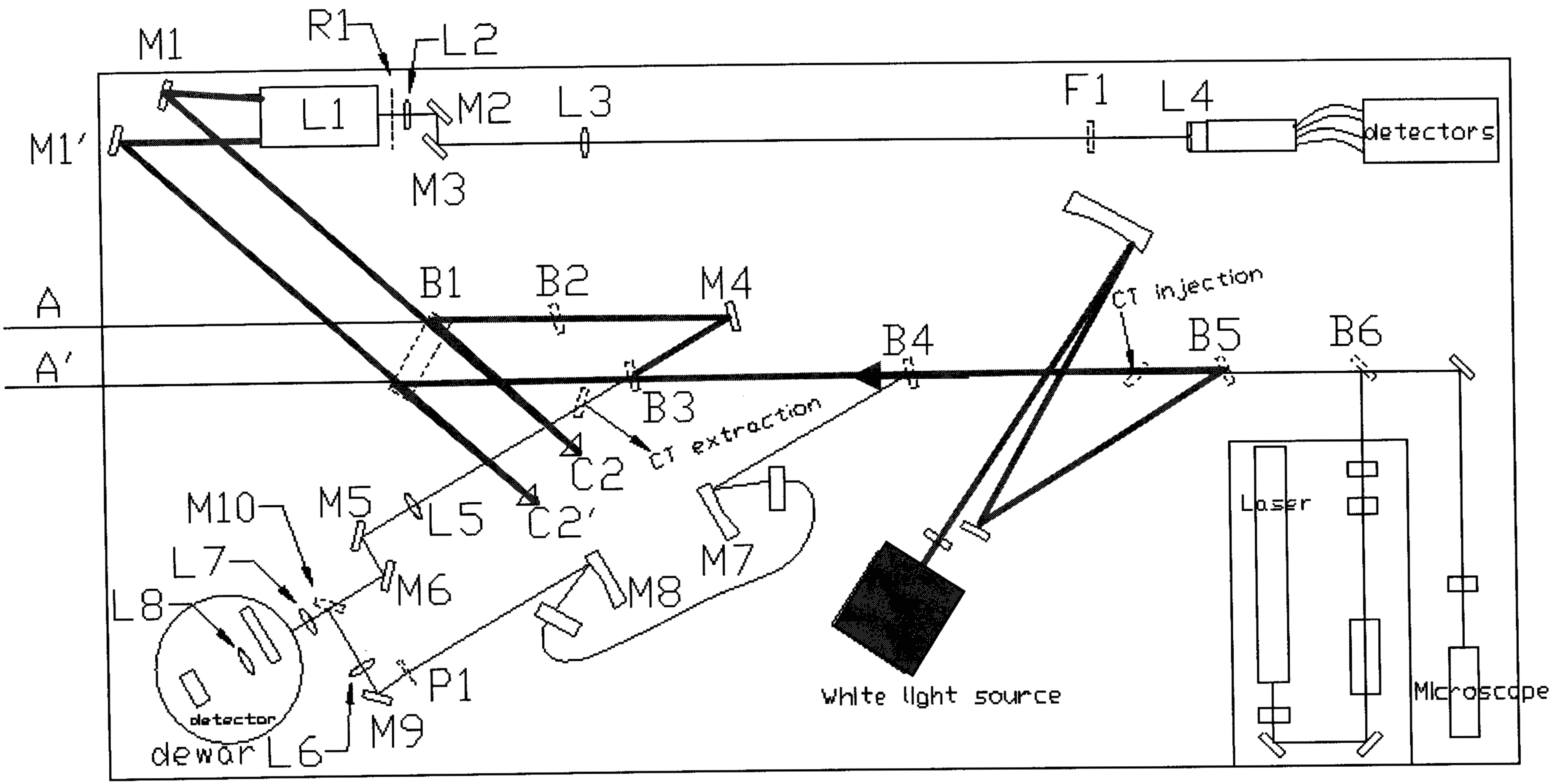
Star tracker optics



Star tracker optics

- Dichroic B1 reflects visible light
- Telescope L1 forms images at field lens L2
- L3 relays image to detector L4
- Detector is quad-cell comprised of
  - Lenslet array to define geometry
  - Fiber-fed photon counting avalanche photodiodes for detector
- One detector - two stars?
  - Mirror M3 is on a 100 Hz chopper, alternating beams on detector head
  - Photon-binning board collects photons
- Filter F1 blocks scattered laser light at $\lambda < 0.7$ um

Setting star tracker boresight



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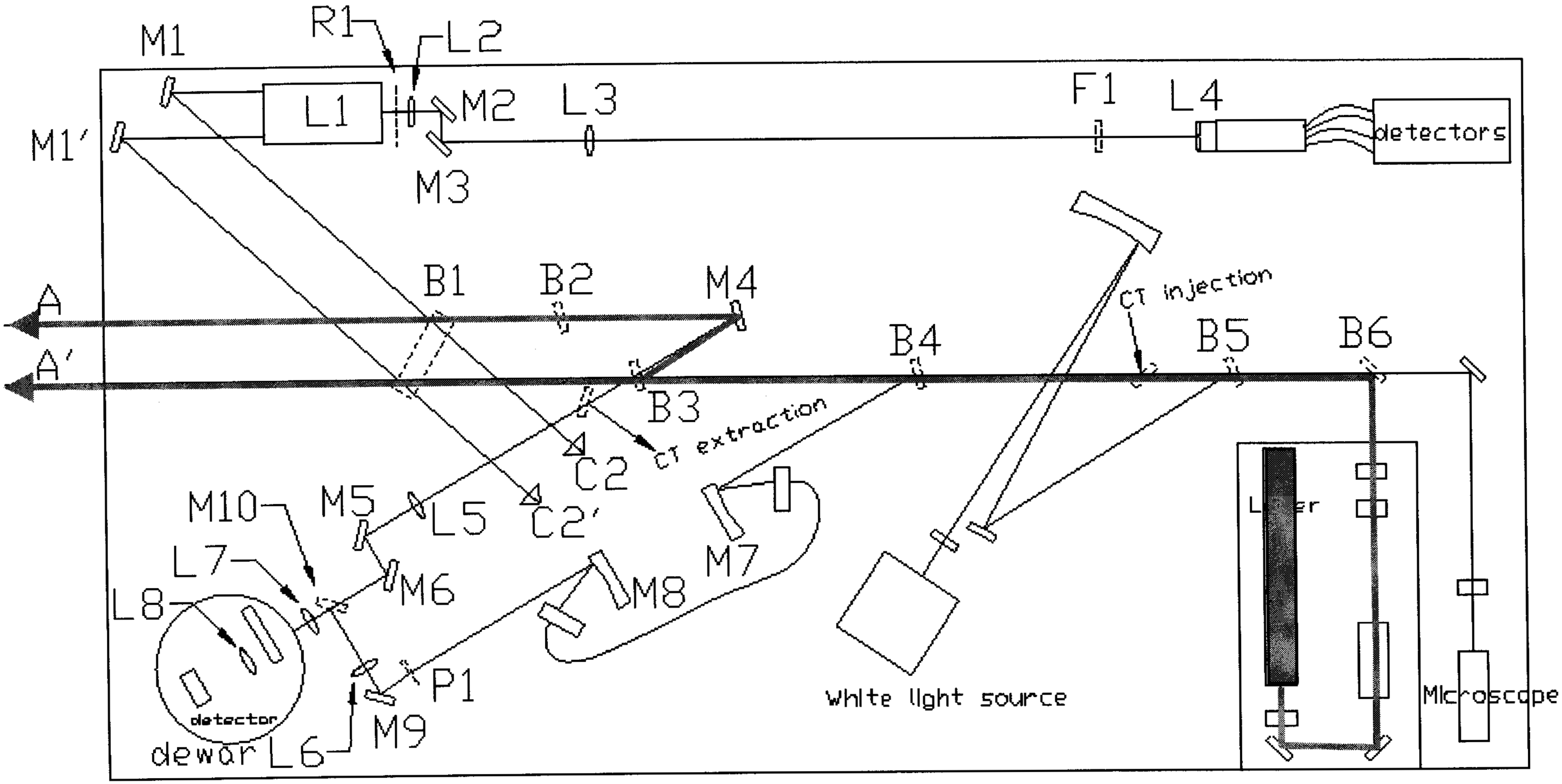
Setting star tracker boresight

- White-light source from combined beam reflects off back of dichroic to produce two images
- Star tracker adjusts zero points to center these two images
  - Adjusts extremes of chop-mirror (M3) travel
- Laser source, boresighted to white-light source with microscope, is also sent out to boresight acquisition system

Setting acquisition boresight



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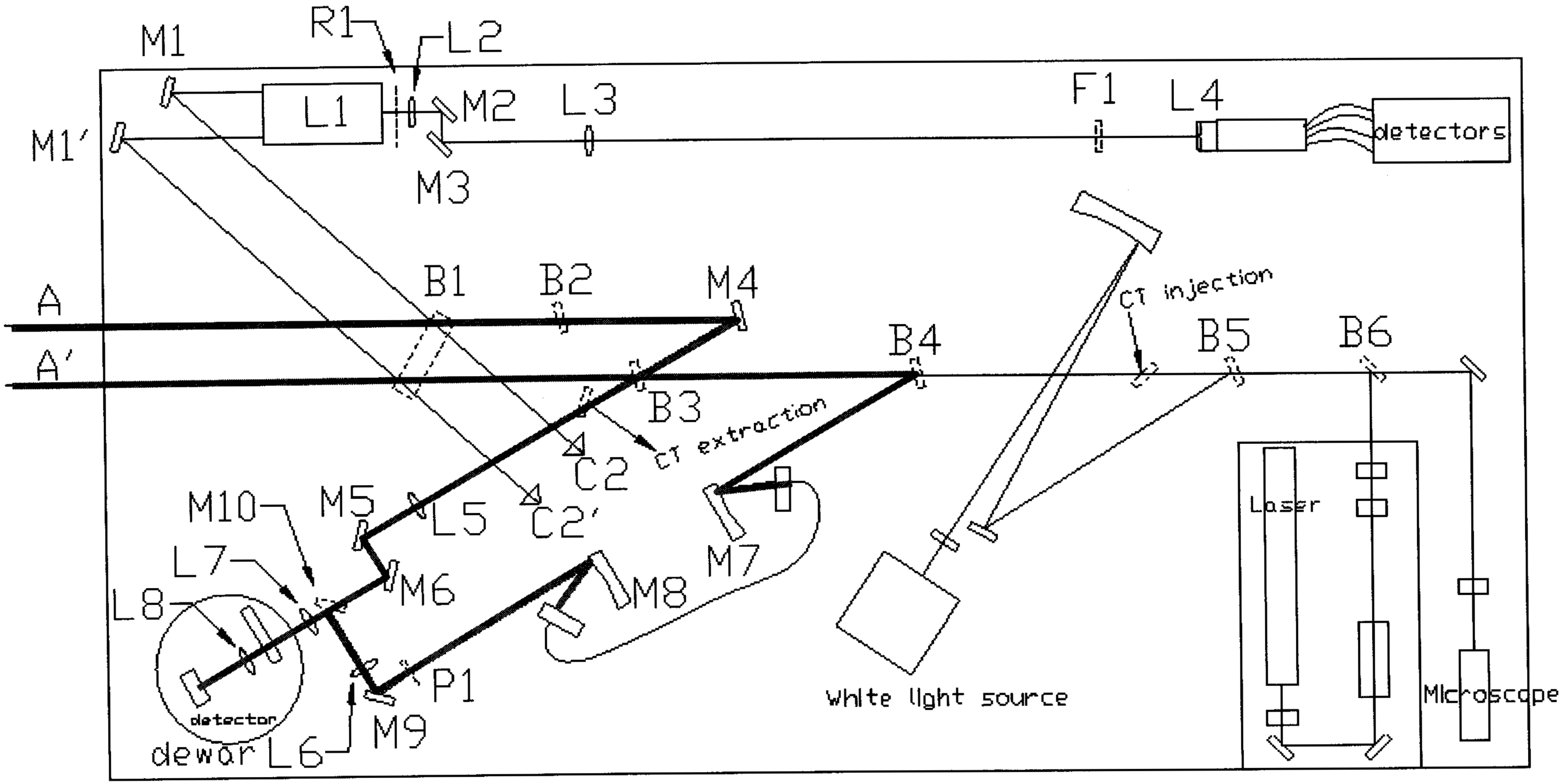
Star tracker functions

- Boresights
- Acquisition
  - Commands siderostat with geometric spiral to place image in FOV
- Tracking
  - Closed-loop tracking using fast-steering mirrors in dual-star feed
  - Optional feedforward to secondary fast-steering mirrors

Fringe tracker optics



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Fringe tracker

- Beams are combined at Michelson beamsplitter B3
- Light is directed to dewar via two paths
  - White-light path
    - » Light is imaged onto a single detector pixel
      - Mean wavelength: 2.2 um
  - Spectrometer path
    - » Light is dispersed with a low resolution prism spectrometer and imaged onto 5-8 pixels
      - Wavelength coverage: 2 - 2.4 um (astronomical K)

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Detector

- Detector
  - NICMOS-III infrared array detector
    - » 4 128x128 quadrants
      - We use 7 pixels on one line (use engineering-grade chips with one or two good quadrants)
    - » Single-read read noise of 32 electrons reduces to ~12-16 with multiple non-destructive reads
- Dewar
  - Contains infrared array, filter wheel

- 2) Fringe visibility tells us about structure of source:

Measuring Visibility

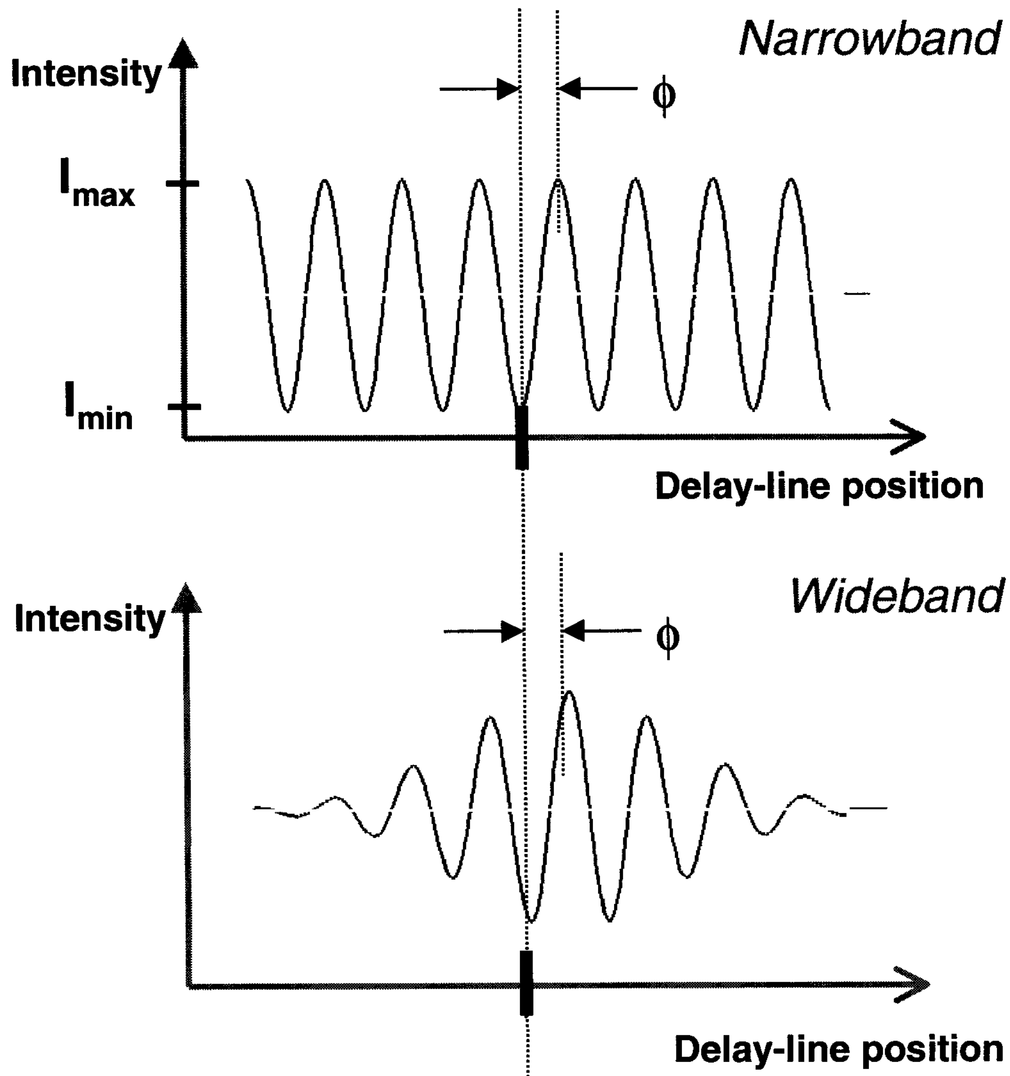
Visibility Amplitude
(or just visibility)

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

$$0 < V < 1$$

- In general, fringe visibility is a complex number

$$\Gamma = V e^{-j\phi}$$

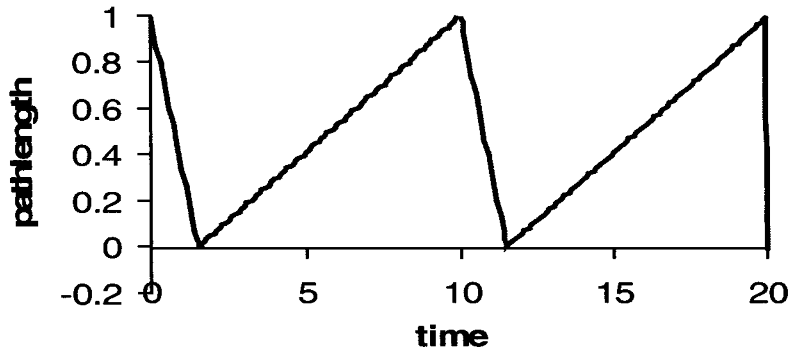


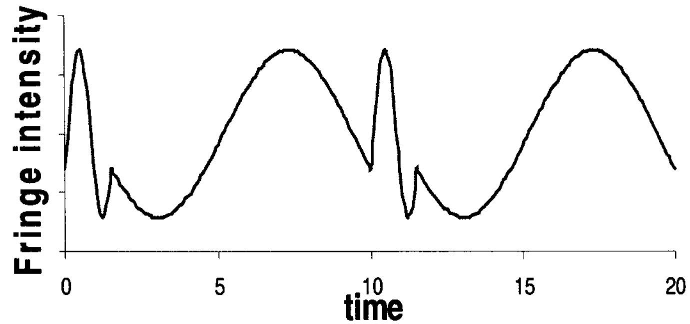
Fringe measurements

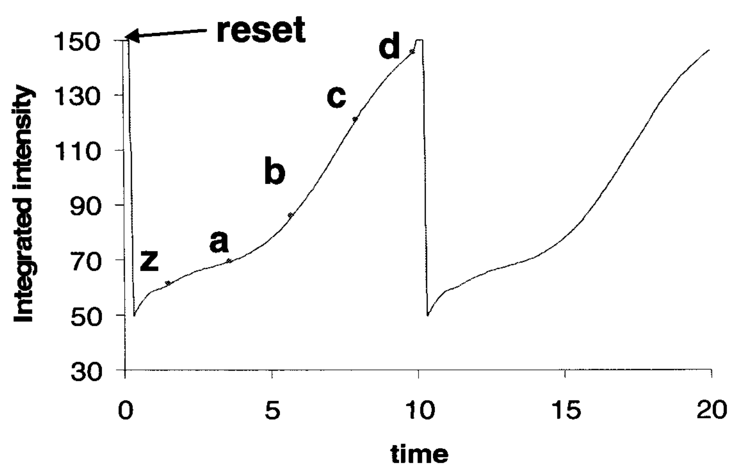
- Fringe-scanning modulation, implemented on delay line
- Sawtooth waveform to minimize number of reads per frame
- Retrace occurs during array settling time
- A, B, C, D bins computed as
  - A = a - z, etc.
- Timing varies with wavelength so that each time bin corresponds to $\lambda/4$ at the wavelength of interest
- Let X = A-C, Y = B-D, N = A+B+C+D

$$\phi = \arctan\left(\frac{Y}{X}\right)$$

$$V^2 \propto \frac{X^2 + Y^2 - \text{bias}}{N}$$







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Servo details

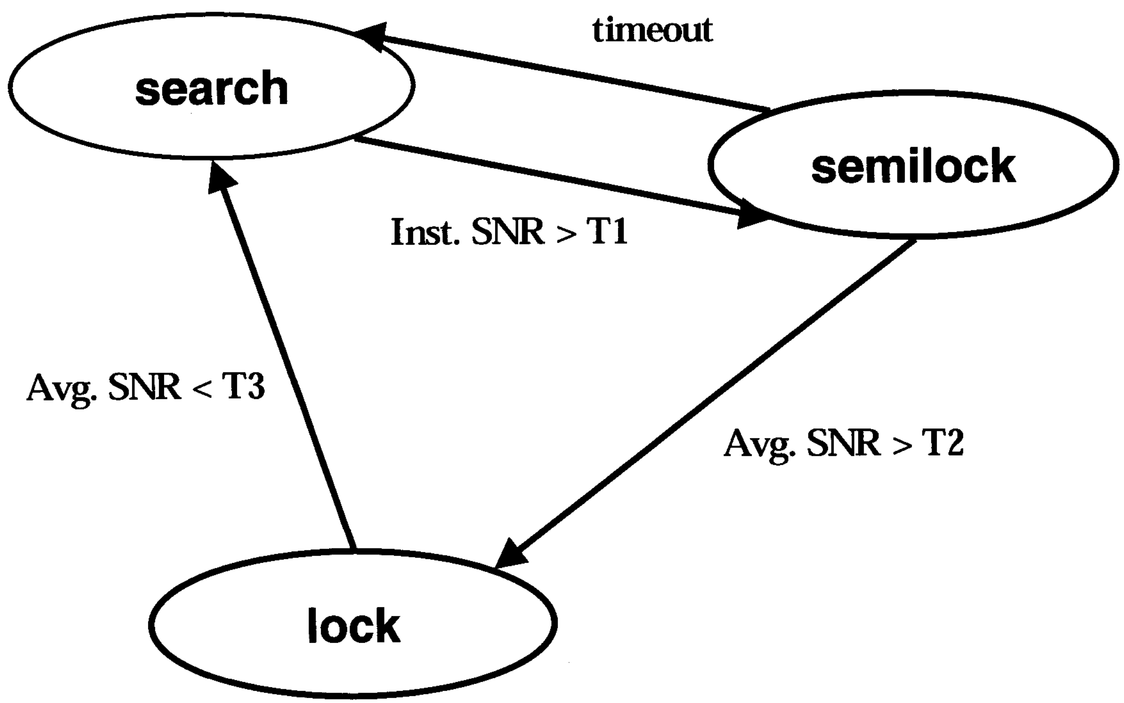
- Fundamental frame time is 10 ms
  - Each 10-ms
    - » Estimate white-light phase
    - » Unwrap white-light phase based on state-space model and history
    - » Closed-loop phase-tracking servo using feedback to delay line
      - 10 Hz bandwidth
    - » Phase reference spectrometer phasors

$$\left\langle \Gamma_i \right\rangle = \sum \Gamma_i \, e^{-\frac{\lambda_{\mathrm{wl}}}{\lambda_{\mathrm{i}}} \phi_{\mathrm{wl}}}$$

  - At a lower rate
    - » Compute group delay - essentially phase slope across spectrometer bands
      - Gives fringe position without 2π ambiguity

Fringe tracker state machine

- Fringe tracker state machine has three states
  - *Search* executes a geometric spiral in delay, looking for signal
  - *Semilock* tries to phase track: if successful…
  - *Lock* tracks the fringe



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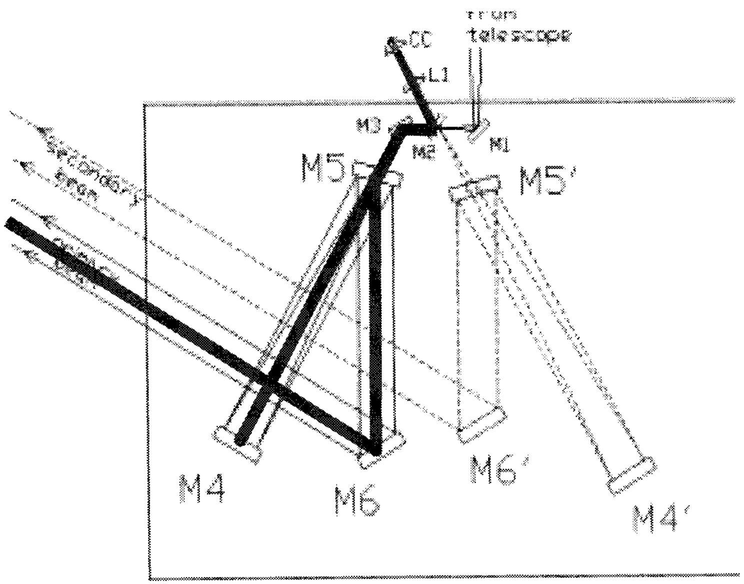
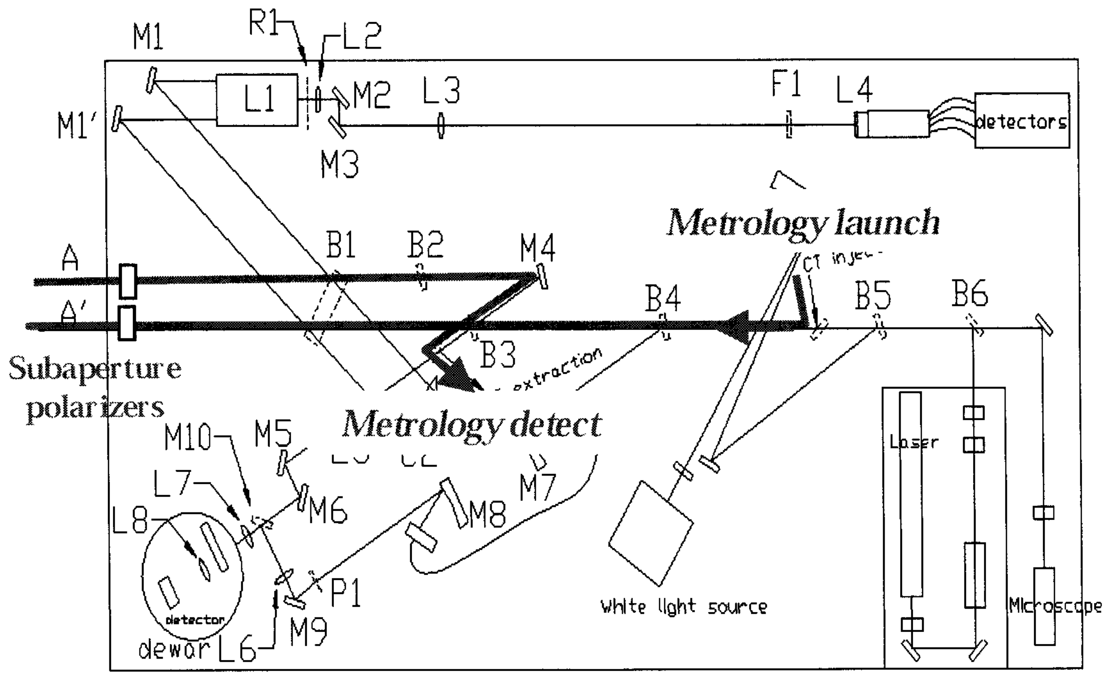
Single-mode fiber

- Single-mode fiber spatial filter inserted in combined beam for spectrometer channels
- Single-mode fiber accepts only one spatial mode
    - » Essentially, rejects light which would not contribute to interference (reduces N, but increases V^2)
- On PTI, has improved our raw spectrometer V^2 by a factor of two
  - Also, with high mean V^2, lower relative fluctuations

Constant-term metrology

Corner cube in dual-star feed





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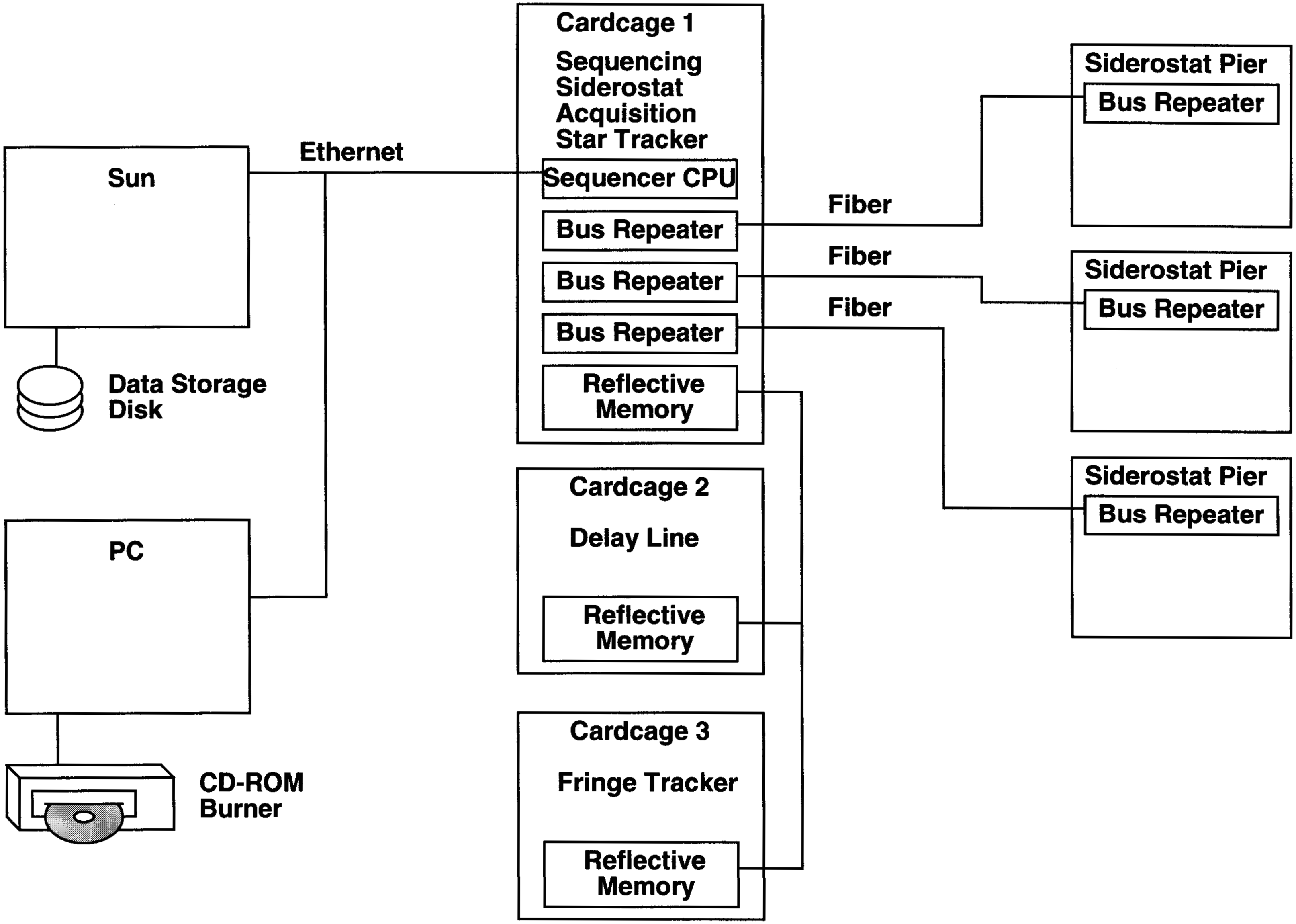
Constant-term metrology

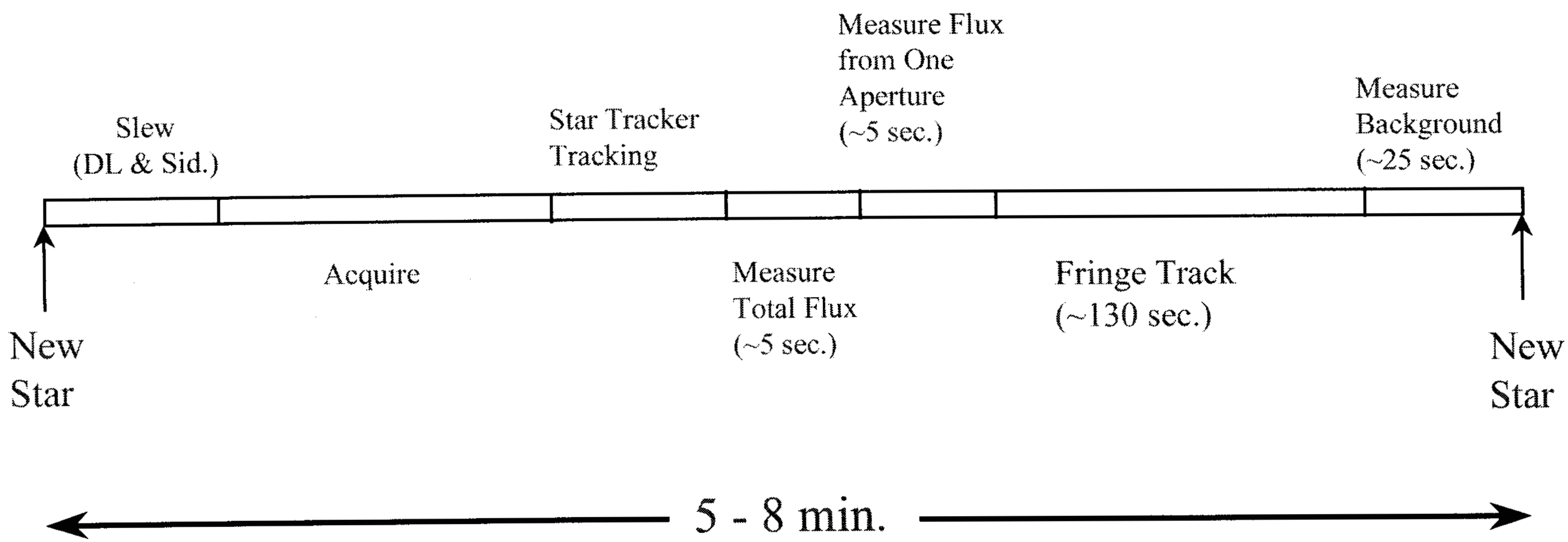
- Measures difference in optical path between the two arms for each beam combiner
  - Difference in metrology measurements between the beam combiners, plus fringe phase, gives star separation
- Heterodyne metrology starting at main beamsplitter to corner cubes at the dual star feed
  - Subaperture polarizers send and *s* and *p* polarizations to different arms
  - Heterodyne at separate carriers to avoid interference between primary and secondary metrology systems


Cardcage 1
Sequencing
Siderostat
Acquisition
Star Tracker
Sequencer CPU
Bus Repeater
Bus Repeater
Bus Repeater
Reflective Memory
Siderostat Pier
Bus Repeater
Siderostat Pier
Bus Repeater
Siderostat Pier
Bus Repeater
Fiber
Fiber
Fiber
Ethernet
Sun
Data Storage Disk
PC
CD-ROM Burner
Cardcage 2
Delay Line
Reflective Memory
Cardcage 3
Fringe Tracker
Reflective Memory

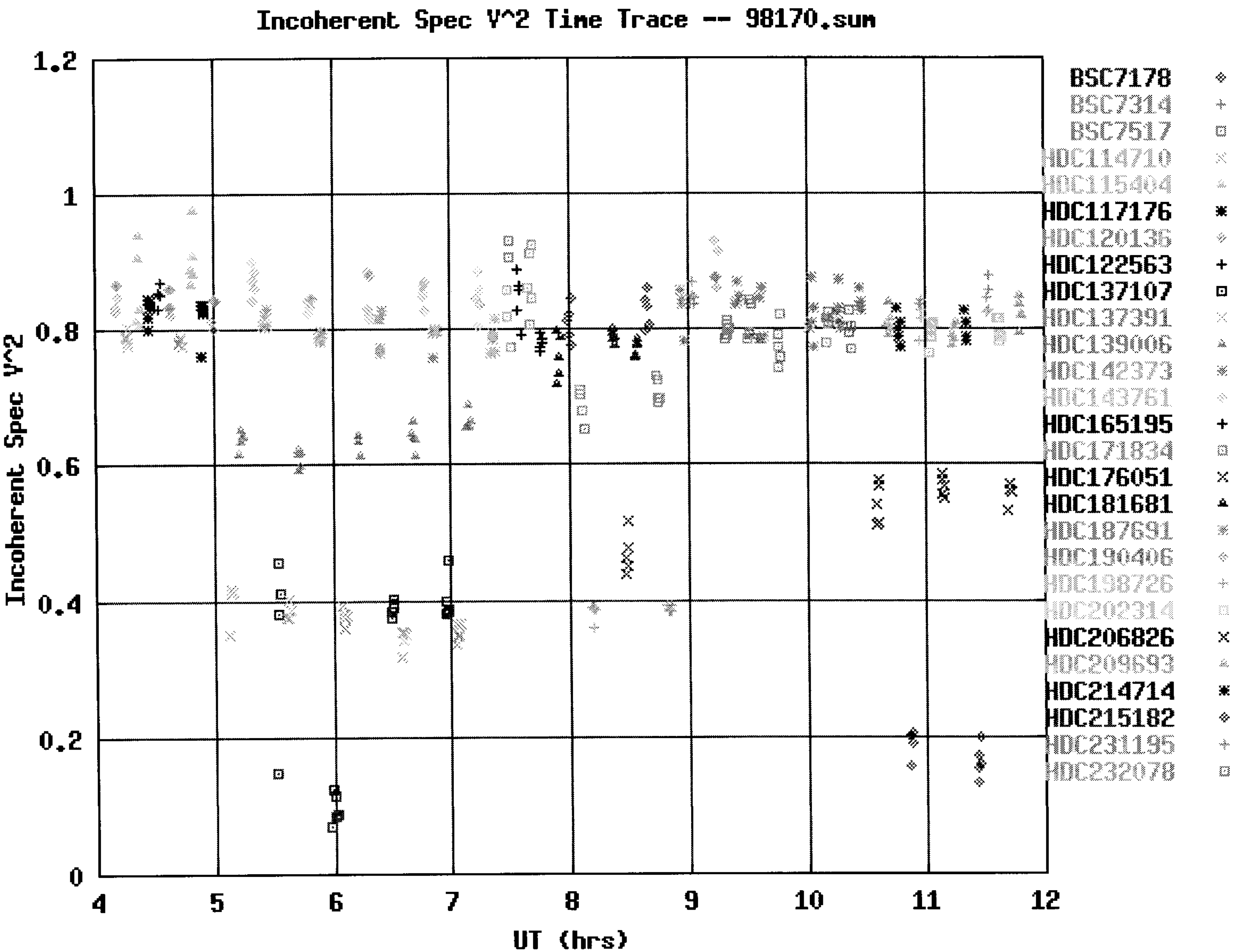
Software and Control System

- VME real-time control system
  - VxWorks, C/C++
  - 7 VME single-board computers in 3 crates
  - Reflective memory for inter-processor communication
- Sun workstation
  - Graphical User Interface
  - Data recording
- Observing Process
  - Observer creates star list
    - » Science objects, calibrations objects, and time per object
  - Highly automated, very efficient
    - » ~100 independent observations per night

Observing Sequence



Sample visibility data



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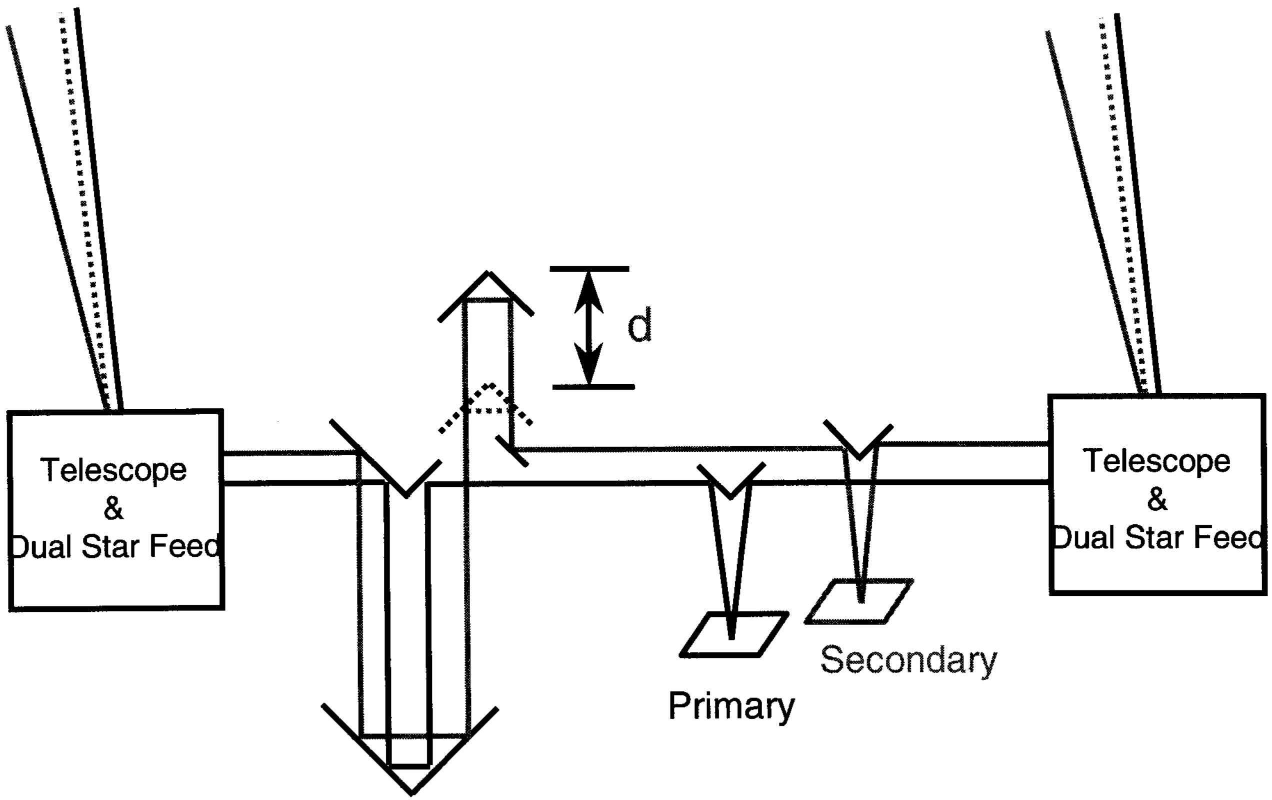
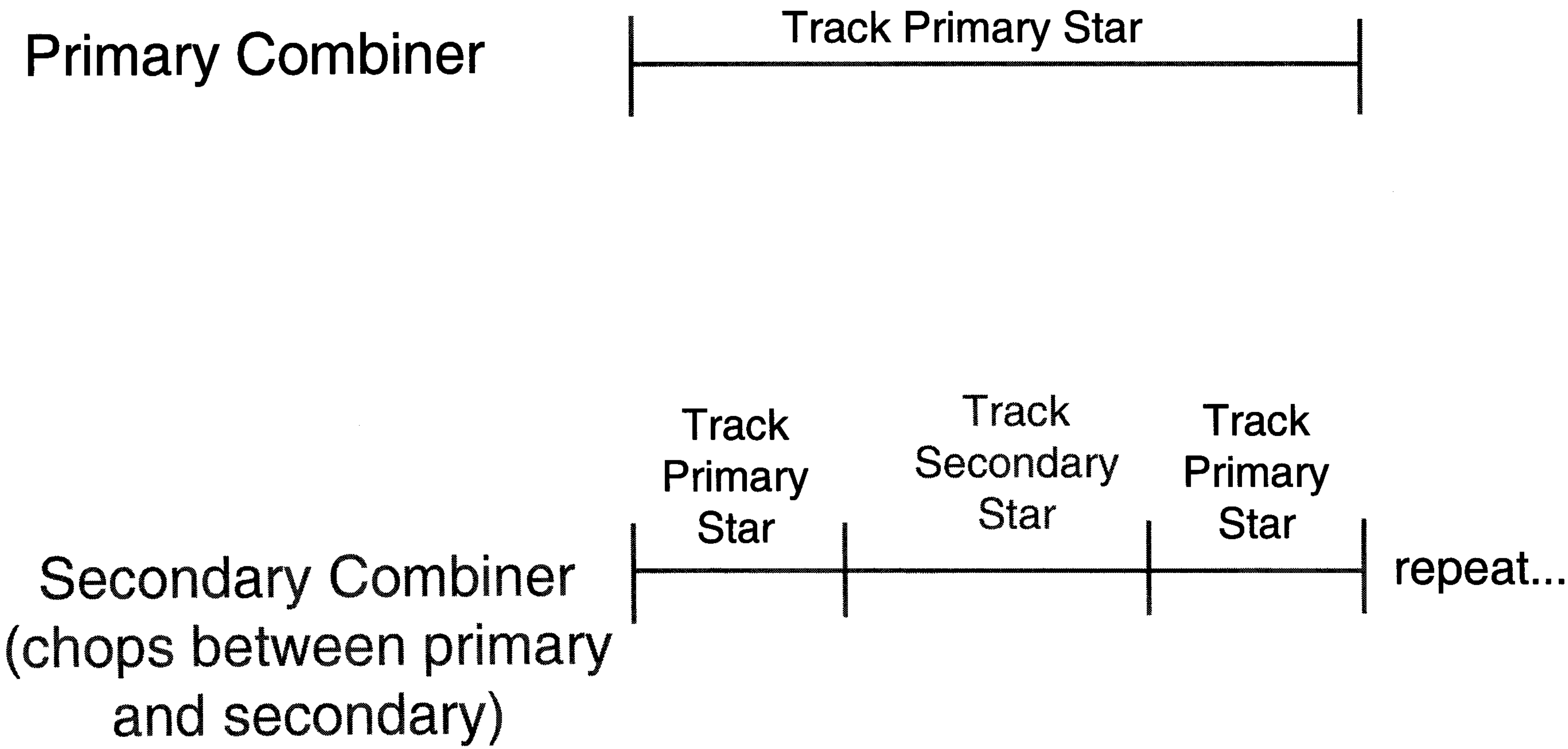
Making a narrow-angle measurement



Differential delay line shown in secondary path for clarity

Astrometry Observation



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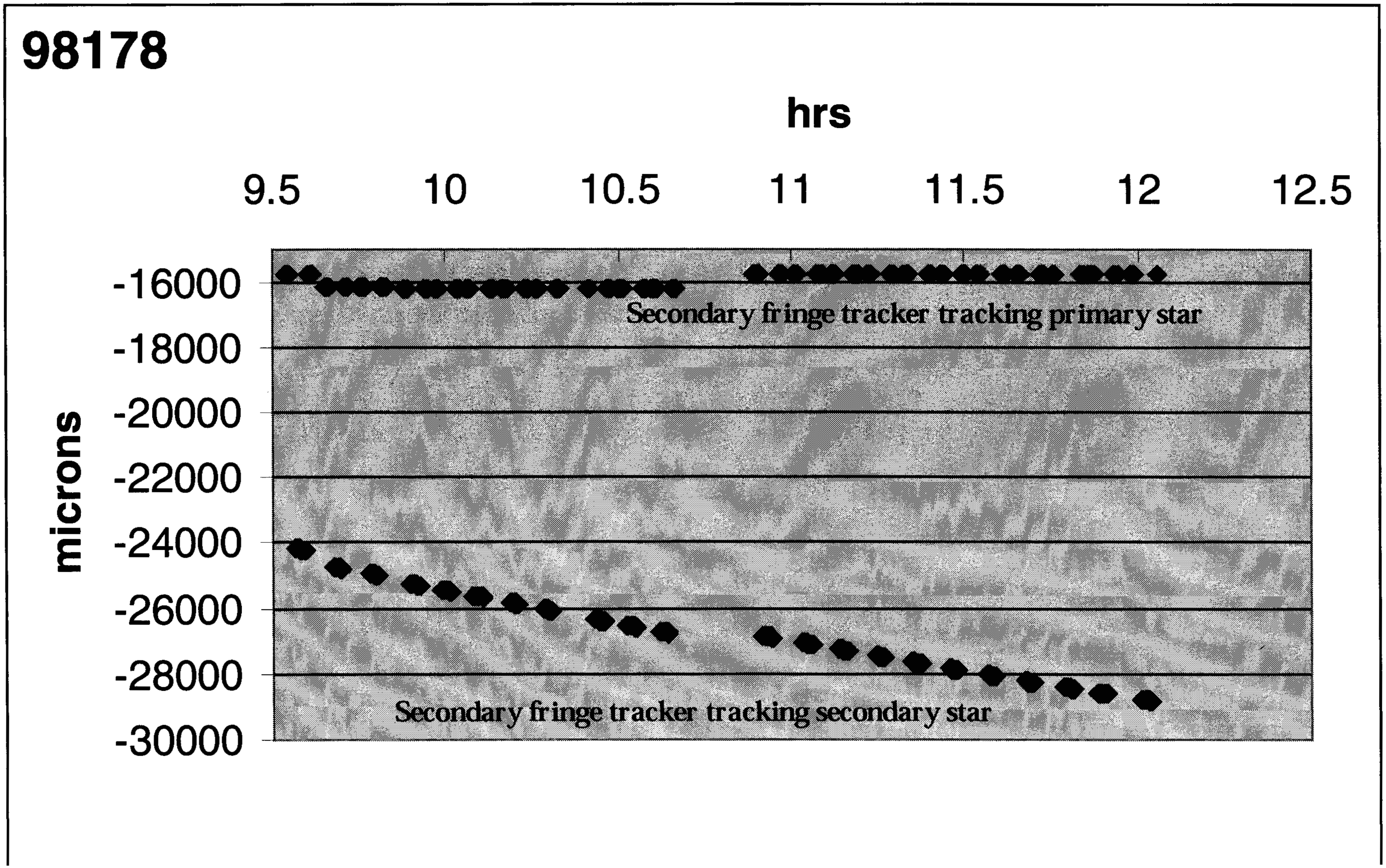
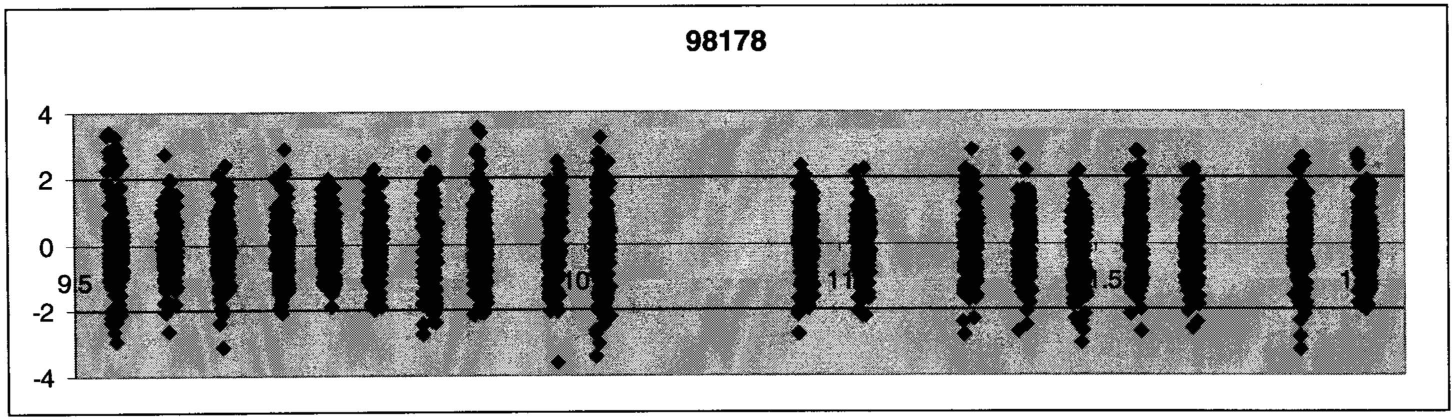
Raw data after outlier removal

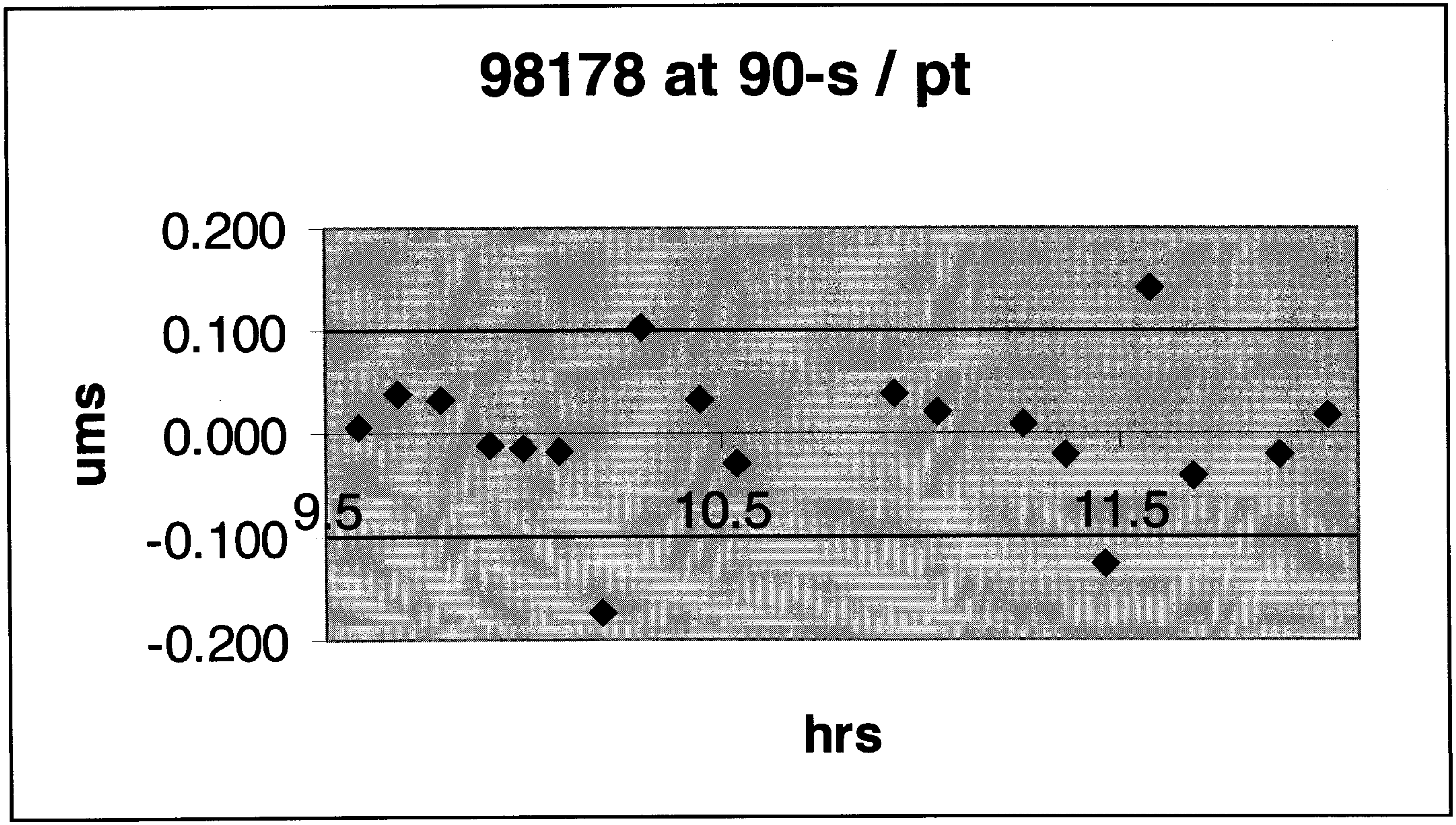


Calibrated data, 0.5-s per point



After removal of best-fit sin, cos, and constant

Averaged data



Internal errors: 70 nm rms; 140 uas rms per 90-sec point

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More info

- http://huey.jpl.nasa.gov/palomar
  - General stuff
  - Follow links to publications for instrument and science papers